

CRANFIELD UNIVERSITY

Ryan Walker

Localising Imbalance Faults in Rotating Machinery

School of Applied Science  
IVHM Centre

PhD Thesis  
Academic Year: 2012 - 2013

Supervisor: Dr. Sureshkumar Perinpanayagam  
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## **ABSTRACT**

This thesis presents a novel method of locating imbalance faults in rotating machinery through the study of bearing nonlinearities. Localisation in this work is presented as determining which discs/segments of a complex machine are affected with an imbalance fault. The novel method enables accurate localisation to be achieved using a single accelerometer, and is valid for both sub and super-critical machine operations in the presence of misalignment and rub faults.

The development of the novel system for imbalance localisation has been driven by the desire for improved maintenance procedures, along with the increased requirement for Integrated Vehicle Health Management (IVHM) systems for rotating machinery in industry. Imbalance faults are of particular interest to aircraft engine manufacturers such as Rolls Royce plc, where such faults still result in undesired downtime of machinery. Existing methods of imbalance localisation have yet to see widespread implementation in IVHM and Engine Health Monitoring (EHM) systems, providing the motivation for undertaking this project.

The imbalance localisation system described has been developed primarily for a lab-based Machine Fault Simulator (MFS), with validation and verification performed on two additional test rigs. Physics based simulations have been used in order to develop and validate the system. An Artificial Neural Network (ANN) has been applied for the purposes of reasoning, using nonlinear features in the frequency domain originating from bearing nonlinearities. The system has been widely tested in a range of situations, including in the presence of misalignment and rub faults and on a full scale aircraft engine model. The novel system for imbalance localisation has been used as the basis for a methodology aimed at localising common faults in future IVHM systems, with the aim of communicating the results and findings of this research for the benefit of future research. The works contained herein therefore contribute to scientific knowledge in the field of IVHM for rotating machinery.



Keywords: IVHM, Rotordynamics, EHM, Neural Network, Misalignment, Machine Fault Simulator.

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## LIST OF DEFINITIONS

**Imbalance** (mass noun): Lack of proportion or relation between corresponding things (Oxford English Dictionary)

**Localise** (verb): Assign (something) to a particular place (Oxford English Dictionary)

**Nonlinear** (adjective): *Mathematics* – designating or involving an equation whose terms are not of the first degree. *Physics* – involving a lack of linearity between two related qualities such as input and output (Oxford English Dictionary)

**Rotordynamics:** A specialised branch of applied mechanics concerned with the behaviour and diagnosis of rotating structures (web definition – Wikipedia)

**Unbalance** (verb): Upset or disturb the equilibrium (Oxford English Dictionary)

## **LIST OF ABBREVIATIONS**

AI: Artificial Intelligence

ANN: Artificial Neural Network

DAQ: Data Acquisition

DOF: Degree(s) of Freedom

DyRoBeS: Dynamics of Rotor Bearing Systems

EHM: Engine Health Management

FEA: Finite Element Analysis

FFT: Fast Fourier Transform

FRF: Frequency Response Function

IVHM: Integrated Vehicle Health Management

MFS: Machine Fault Simulator

ODS: Operating Deflection Shapes

SAGNN: Self Adaptive Growing Neural Networks

STFT: Short Term Fourier Transform

TTL: Transistor-Transistor Logic

VAC: Voltage in Alternating Current



## LIST OF PUBLICATIONS

**Note:** The following papers have undergone review and have been published or accepted for publication at the time of thesis submission. A number of additional works are pending review.

Walker, R., Perinpanayagam, S. and Jennions, I.K. (2011), “Physics-Based Simulation for Health Management of Rotating Machinery”, *The Eighth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies – CM/MFPT*, BINDT, Cardiff, 20-22 June 2011, vol 1.

Walker, R. Perinpanayagam, S., Jennions, I.K., 2012, “Simulating Unbalance for Future IVHM Applications”, *The 2012 International Modal Analysis Conference*, SEM Inc., Jacksonville, February 2012, vol 4, pp 141-148.

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Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, “Rotordynamic Faults: Recent Advances in Diagnosis, Prognosis and Localisation”, *International Journal of Rotordynamics*, vol. 2013, 12 pages.

Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, “Localizing Unbalance Faults in Gas Turbines”, *ASME Turbo Expo 2013*, ASME, San Antonio, June 2013, Publication Pending.

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Ewins, D.J. (2000), *Modal Testing: Theory, Practice and Application*, Research Studies Press, UK

Jennions, I.K, *Integrated Vehicle Health Management*, 1<sup>st</sup> ed, SAE International

Lees, A.W (2002), *Machine Vibration Signature Analysis*, 1<sup>st</sup> ed, Research Studies Press Ltd, UK

Muszynska, A. (2005), *Rotordynamics*, 1st ed, Taylor & Francis, UK

Worden, K. and Tomlinson, G.R. (2001), *Nonlinearity in Structural Dynamics: Detection, Identification & Modelling*, 1<sup>st</sup> ed, Institute of Physics Publishing, UK

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# 1 Introduction

Rotating machinery continues to fill an important role in the modern world. With applications including power generation and transportation, the importance of such machinery cannot be overestimated. As we move towards a future where the efficiency and reliability of these machines are continually being stretched, investigating ways in which we can improve the operation of some of the most important machines in use becomes more and more relevant.

Taking the aircraft industry as one example, as the world strives for cheaper and more efficient connections across the globe, the demands on aircraft operations increase. Keeping aircraft in the air by minimising unscheduled, and indeed scheduled, maintenance times is beginning to become an increasingly important consideration for manufacturers such as Rolls Royce plc. Similar relevance can be applied to the power generation, marine and automotive environments. The study to make these improvements in next generation systems is covered by Integrated Vehicle Health Management (IVHM).

Rotating machinery can be subject to a wide range of potential failure methods. One of the most common issues which can occur in such machines is imbalance faults. Rotating machinery typically operates within a fine balancing tolerance, as the gyroscopic forces exerted on such systems can be great and potentially amplified to undesirable levels when excessive unbalance is applied. Such faults can be caused by a wide range of phenomena. In aircraft, severe issues ranging from fan blade off to blade cracks, build-up of deposits and incorrect balancing are some of the reasons for imbalance faults.

Since the inception of rotating machines, a wide range of research has been, and continues to be, published on the subject of diagnosing common faults. The diagnosis of imbalance has seen a large amount of research, yet despite this, relatively few studies have provided practical solutions to the problem in complex rotating machines. Many systems for diagnosis use complex, intrusive sensor suites in order to achieve accurate diagnosis. In addition, few of these studies are able to accurately locate imbalance faults within complex

machinery. Within this study, 'localisation' refers to determining which discs/segments of a machine are affected with an imbalance fault (as opposed to locating imbalance on a single disc for the purposes of balancing a machine).

Whilst the ability to diagnose imbalance faults has clear advantages, in order to meet the aims of improved maintenance operations it is important that technicians have access to information on not only the nature of any faults, but also their location. This enables costly procedures to be minimised, by allowing maintenance teams to proceed directly to the location of the fault.

The current state of the art in localising imbalance faults typically involves model-based approaches, in which knowledge of the operating mode of the system is known, and therefore imbalance position may be inferred through the response detected at several points. Such systems have found use in the power generation industry, where multiple sensors and flexible machine operation enable such systems to be used. Clear limitations of these localisation approaches include the requirement for multiple sensors, flexible operating regimes and accurate models. As such, their applicability in certain rotordynamic systems (such as aircraft engines) is limited.

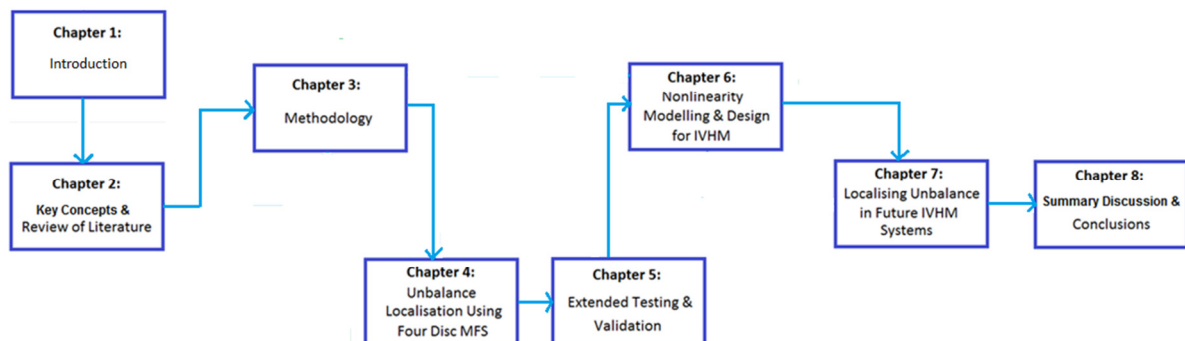
In order to make any system for diagnosing and localising imbalance faults practical for future development and implementation, it is important that they can operate with a sensor and instrumentation suite which is both physically practical and cost effective. The use of both simulation and experimental approaches are prevalent in the diagnosis of faults in rotating machinery, and as such it is important to consider both aspects in solving the presented problem. Finally, it is important to present any research performed in a form which can aid future developments in maintenance of rotating machinery. In this way, significant benefits can be provided for the field of IVHM – meeting the demands which are being placed on rotating machines in service today and tomorrow.

As such, the development of a novel system for imbalance fault localisation represents both a contribution to scientific knowledge and a high relevance to industrial application. This work therefore aims to answer the following:

## Research Questions:

- Can a novel system capable of accurately localising imbalance faults in rotating machinery be developed, relying on a minimal, non-intrusive sensor suite and capable of operating under a wide range of conditions?
- How can a synergy between physics-based simulation and data-driven approaches aid imbalance localisation?
- Can imbalance localisation be accurately performed when additional faults exist within the system?
- Is it possible to create a general methodology for imbalance localisation, taking into account potential application in next generation IVHM systems?

In order to answer these questions, research has been conducted using a combination of simulation techniques, culminating in the use of specialist rotordynamic software. Experimental results have been collected using a Machine Fault Simulator (MFS), sold by Spectraquest, fitted with four discs and a number of accelerometers (although the final, developed system only requires one for operation). Automating the fault classification has been done through application of an Artificial Neural Network (ANN), and validation has taken place by adapting the system to work with two additional test rigs. Finally, the research is aimed at generating recommendations for future developments into rotating machinery aspects of IVHM. In order to communicate the findings of the research, this work has been laid out as follows:



**Figure 1-1** Thesis Layout

To begin, a study of existing work is covered in Key Concepts & Review of Literature (Chapter 2). Based upon this, the research questions have been formed and a Methodology (Chapter 3) has been created for answering these. The experimental work begins with Imbalance Localisation Using Four Disc MFS (Chapter 4), whereby the first research question is tackled. The developed method for localising imbalance faults then undergoes Extended Testing & Validation (Chapter 5), using two additional rotordynamic rigs and answering the second research question. The third research question is answered through Nonlinearity Modelling and Design for IVHM (Chapter 6), in which the simulation and data-driven approaches are brought together. The findings from the practical aspects of the research are discussed as Localising Imbalance Faults in Future IVHM Systems (Chapter 7). This places the research into the broader picture and answers the final research question. This in turn leads to the Summary Discussion (Chapter 8) and Conclusions.

In pursuit of answering the research questions posed, a number of novel aspects have been developed. These can be summarised as follows:

**Primary Novel Aspect:** A new method for localising imbalance faults in rotating machinery has been developed.

Based upon machine nonlinearities and utilising a single accelerometer, the new method has been shown to provide accurate results across three rotordynamic test rigs and under a wide variety of operating conditions – including rigid and flexible operating regimes and in the presence of misalignment and rub faults.

**Secondary Novel Aspects:** During the development of the novel method, the following secondary novel aspects have been detailed:

- The correlation between a bearing clearance nonlinearity and imbalance position has been simulated. Demonstrating the theory behind the proposed imbalance localisation system (Chapter 6)
- A full scale aircraft engine model has been used to demonstrate the potential for imbalance localisation in a scaled-up system (Chapter 6)

- The study highlights some reasons why much current research into imbalance faults in rotating machinery is impractical for application in next generation IVHM systems. Key points to address this imbalance have therefore been highlighted (Chapter 7)
- Two graphical methodologies for creating an imbalance localisation system in future IVHM applications have been developed (Chapter 7)

These novel aspects to the project appear in a number of peer-reviewed conference and journal papers (see Appendices).

## **2 Key Concepts & Review of Literature**

### **2.1 Chapter Introduction**

The area of diagnosing and prognosing faults in rotating machinery is an on-going subject of research, with many developments annually published in a range of conferences and journals. This research has the potential to become even more relevant in the coming years due to the rise of IVHM, in which the drive towards condition based maintenance and whole vehicle monitoring plays a vital role. With this in mind, a review of the current state of the art is beneficial as a platform for developing a novel system for localising imbalance faults.

Throughout this chapter, topics of interest to the research conducted in this project have been detailed. This takes the form of key ideas being presented, from industry standard approaches to classic texts and state of the art research being conducted across the community at the current time. The intention of such a study is to highlight the current state of the art to form an understanding of why the research is relevant.

In order to achieve this, the chapter has been divided into sections for the following: Concepts & Basics, Rotordynamic Faults, IVHM & Rotordynamics and Concluding Discussion. Further to the overview given here, additional information is presented in the relevant chapters in order to aid the context of the work being performed.

Due to the huge volume of work which is being performed across the research community into various aspects of rotordynamics, IVHM and other key topics, it is not possible to list all interesting or relevant works within the scope of this chapter. As such, a selection of important and relevant works have been detailed, alongside summaries of general trends in the research community. The aims and objectives of this chapter are as follows:

- Generate an understanding of key knowledge required for the work performed throughout this project.
- Perform a comprehensive review of the current state of the art in diagnosing and prognosing common rotordynamic faults.



- Highlight the requirement for a new methodology for the localisation of imbalance faults in rotating machinery.

## 2.2 Concepts and Basics

The following section describes some of the key concepts and ideas behind the work performed in this document. Where relevant, references to external reading are made for the benefit of the reader. The concepts discussed throughout this section form the backbone of any study into diagnosing and prognosing faults in rotating machines.

### 2.2.1 Linear Rotordynamics: Equation of Motion

In the most basic sense, a simple single rotor system can be described mathematically as follows. The equation is listed in generalised matrix form, and assumes a constant spin speed for a rotor that is symmetrical about the axis of spin. It is assumed that the rotor has a small imbalance and displacement.

$$\mathbf{M}\ddot{\mathbf{q}}(t) + (\mathbf{C} + \mathbf{G})\dot{\mathbf{q}}(t) + (\mathbf{K} + \mathbf{H})\mathbf{q}(t) = \mathbf{f}(t) , \quad (2-1)$$

Equation 2-1 shows the equation of motion, where  $\mathbf{q}(t)$  is a vector containing generalised coordinates,  $\mathbf{M}$  is the symmetric mass matrix,  $\mathbf{C}$  is the symmetric damping matrix,  $\mathbf{G}$  is the symmetric gyroscopic matrix,  $\mathbf{K}$  is the symmetric stiffness matrix,  $\mathbf{H}$  is the symmetric circulatory matrix (inertial damping and linear fluid film damping) and  $\mathbf{f}(t)$  is a time dependant forcing function. Most flexible machines can be considered as beam-like structures, and it is important to note that in a rotating system part of the forcing function is generated by the inherent imbalances which are, therefore, important to this equation.

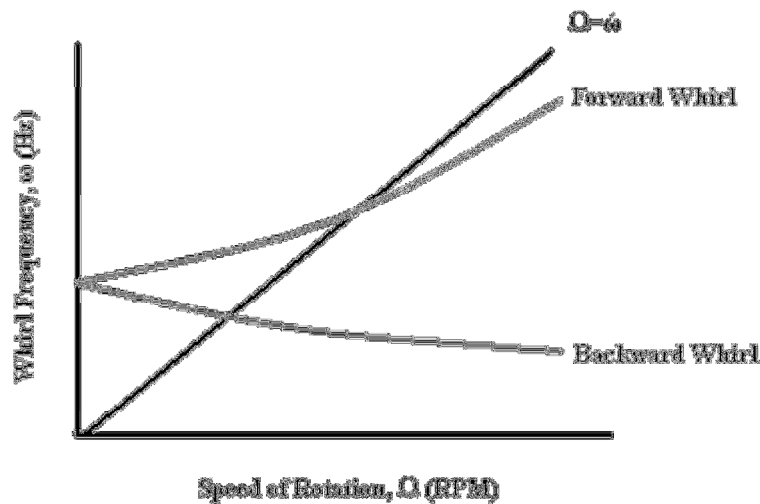
Assuming that the rotor and stator are isotropic with respect to the axis of rotation, complex coordinates can be used to create simple models. If the axis of rotation is said to be in the  $z$ -axis, displacement of any point on the rotor can be described in terms of a displacement vector in the  $xy$  plane, as detailed in Equation 2-2, where  $r(t)$  is displacement with respect to time:

$$\mathbf{r}(t) = \begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix} \quad (2-2)$$

Such complex-coordinates are important in ‘Jeffcott rotor’ models and higher order systems, detailed in 1.2.3 (Genta, (2005)).

### 2.2.2 Campbell Diagram

It can be noted that the speed of rotation of a system appears in the equation of motion (Equation 2-1), and therefore the natural frequencies of a rotor-stator system can be dependent on the speed of rotation. It is useful in rotordynamics to plot natural frequencies and exciting forces as functions of rotational speed, thus producing a Campbell diagram. As stated above, imbalance can act as a forcing function, the frequency of which depends upon the speed of rotation. Thus, this can also be added to a Campbell diagram represented by the straight line whirl frequency = speed of rotation. An example of a simple Campbell diagram of a rotor-stator system is detailed in Figure 2-1.



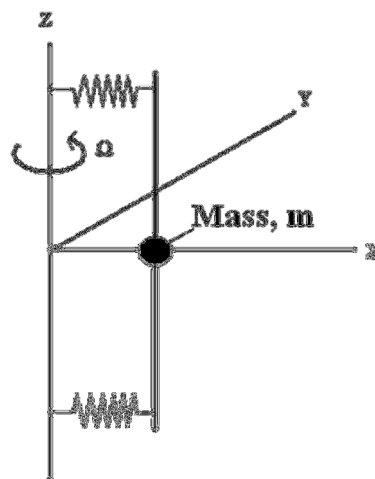
**Figure 2-1** Campbell Diagram

The divergence observed from a single natural frequency is interpreted as two circular whirling motions, one in the direction of rotation and one opposite to this, commonly known as forward and backward whirling respectively. At the points where the forcing function intersects the natural frequencies a resonance

can occur, these points are often referred to as critical speeds. It is important to note that not all critical speeds result in dangerous resonances, if the forcing function is uncoupled from the part experiencing a natural frequency little or minor resonance will occur (Boyce, (2012)).

### 2.2.3 Jeffcott Rotor

The most basic rotordynamic model consists of a point mass attached to a massless shaft. This is commonly known as a 'Jeffcott Rotor' or 'De Laval Rotor', and refers to a lumped parameter method used to solve the equations of motion.



**Figure 2-2** Jeffcott Rotor

Figure 2-2 displays an example of a Jeffcott rotor. With a stiff shaft running on compliant bearings. Three important assumptions have been made in this case, that the system is undamped and that it is axially symmetrical. For this to be the case, the mass,  $m$ , must always lie on the  $xy$  plane (in reality, such 'perfect symmetry' does not exist). It has also been assumed that the speed of rotation is constant.

The Jeffcott rotor system can be used to determine critical speeds. As the disc has an eccentricity about its centre of gravity (an imbalance) the shaft (or, as in the case above, the bearings) deflect elastically. By calculating this deflection as a function of the speed of rotation, critical speeds can be determined. In such

a Jeffcott model the critical speeds will result in infinite deflection, which of course is not possible in an actual rotating machine – however these resonances can potentially be so large as to cause severe damage to a system. By considering and allowing for critical speeds, such basic models have been developed in order to allow modern systems to be designed to operate above one or more critical speeds. It is possible to introduce damping into a Jeffcott rotor system, which will reduce the maximum amplitude of deflection in accordance with the damping coefficient. For an extensive guide to Jeffcott rotors from a mathematical modelling perspective, the reader is referred to the extensive works by Kramer, (1993), Genta, (2005) and Muszynska, (2005). These basic concepts underlie the modelling and theory undertaken throughout this work, particularly in Chapter 3 and Chapter 6.

#### **2.2.4 Time, Frequency & Combined Domains**

The analysis of data for the purposes of identifying rotordynamic faults consists of many aspects. However, it is possible to group methods of displaying collected data into three distinct approaches: Time Domain, Frequency Domain and Combined Time-Frequency Domain. Each of these approaches has specific advantages and disadvantages, however all appear within modern methods for rotordynamic fault analysis.

Whilst the bulk of work within this thesis is undertaken in the frequency domain, certain aspects (e.g. transient analysis in both the modelling and experimental sections) refer to the time domain. Other researchers use the joint time-frequency domain, making it necessary to understand the use of all three approaches.

Time domain methods (typically) detail the vibration characteristics of a machine over the course of time. What is termed ‘slow roll’ data can be important in the diagnosis of certain faults – including rub & looseness.

Frequency domain methods provide a common and much researched method of analysing vibration data. The power of modern computing enables Fast Fourier Transforms (FFT) to be constructed and interpreted with increasing

speed and accuracy. Frequency domain information is used in many applications to detect a wide range of rotordynamic faults, and research is still being performed into improving and expanding the capabilities of frequency domain analysis.

Joint Time-Frequency Domain analysis is a more recent approach to signal processing, and it is useful for interpreting vibrations for which the frequency will vary over time. Methods of expressing time-frequency domain analysis include; Short Time Fourier Transforms, Wigner Distribution Function, Wigner-Gabor Transforms, Time Varying Autoregressive Models, Choi-Williams Distribution, Hilbert-Huang Distribution and Continuous Wavelet Transforms. An excellent comparison of the above techniques for rotordynamic vibration signal analysis is provided by Xiong and Zhang, (2008).

## **2.3 Rotordynamic Faults**

In order to fully understand and summarise the trends and developments in this area, several hundred recent conference and journal papers have been studied. Overall trends have been highlighted and discussed alongside specific papers of relevance. It is intended that this work should form a broad reference and summary in order to highlight specific gaps in research where novel aspects could be developed. Papers with high industrial relevance and which are considered important in the drive towards future IVHM systems have been selected throughout this section.

In order to fully study the diagnosis and prognosis of rotordynamic faults, it has been deemed necessary to break down the topic into the following sections, defined as follows:

**Sensors:** Sensors commonly used for diagnosis of specific faults.

**Fault Identification:** Diagnosis and root cause detection.

**Localisation:** Locating a specific fault within a complex system.

**Prognosis:** Prognosis of components and remaining useful life.

**Modelling:** Simulation of rotordynamic faults.

Through the study of the topics listed, it is useful to place the research conducted in this chapter into context with regards to real-world applications. Further to this, it is intended to identify potential areas where more research is required in order to push some of the recent technologies highlighted for this study into industry.

Andresen, (2006) provides a summary of maintenance time breakdown for a collection of military aircraft. This indicates that as much as 44% of on-aircraft maintenance time (which in turn accounts for 90% of total maintenance operations) is consumed with inspection alone. The techniques addressed in this paper enable the maintenance to be more informed and targeted, with inventory ready when needed, providing a significant contribution to reducing maintenance time and cost.

As the topic of rotordynamic faults is very large area of research, the scope of this research has to be limited. The choice of faults has been made after considering the works by Muszynska, (2005) and Bently, (2002), both of whom consider the fundamentals of common faults in much detail. Out of the wide range of possible rotordynamic faults, eight have therefore been selected. Due to the general reliability of the current generation of gas turbines, faults falling outside of the eight listed have been classed as 'uncommon' for the purposes of this study. This decision was made by assessing the severity of each fault, dependences on other faults and the level of research dedicated to diagnosis of each fault.

Whilst imbalance is the main topic of research within this thesis, it is necessary to consider the other seven common faults. Each fault presents a link to imbalance, as either an underlying cause or a secondary fault (in addition to being individual faults in their own right). Furthermore, a number of the common rotordynamic faults and their effects appear throughout this work. Studying diagnosis and localisation of other common rotordynamic faults also presents relevance to this work due to understanding different systems that exist, and how these may be adapted to the case of imbalance. Finally, in order to achieve

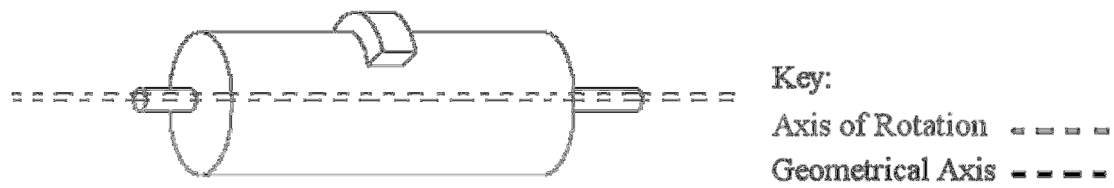
the stated research question “Can imbalance localisation be accurately performed when additional faults exist within the system?” it is necessary to study the current state of the art in these faults.

### 2.3.1 Imbalance

Imbalance is one of the most common rotordynamic faults (Bently, (2002)); All rotating machines contain an inherent amount of imbalance, through causes such as nonhomogeneous materials, manufacturing tolerances and assembly procedures. Rotating machines therefore operate after balancing has been performed in order to bring this to within a given tolerance. The fault ‘imbalance’ can therefore be considered as an imbalance occurring outside of this given tolerance. Such conditions can be caused by a wide variety of phenomena. Taking the example of a gas turbine, imbalance may be caused by a build-up of material on compressor or turbine discs, blade damage (ranging from small cracking/chipping to full blade-off) and incorrect/inaccurate maintenance/balancing procedures - to name but three examples. The importance of understanding and negating imbalance in rotating machines has been highlighted by a number of authors. Domes, (2008), as an example, provides a thorough review from the perspective of Rolls Royce.

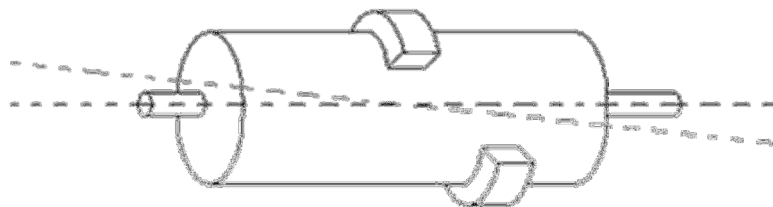
Imbalance as a fault has been studied extensively in literature for many years. In a basic sense, imbalance often manifests itself through excessive 1X (synchronous) vibrations. Through the different mechanisms which cause imbalance, it can manifest itself in several ways. The different imbalance mechanisms applied through this thesis can be seen as follows: (McMillan, (2004)):

- **Static Imbalance:** The simplest form of imbalance as detailed in Figure 2-3. The centre of rotation is displaced parallel to the geometric centre of the rotor.



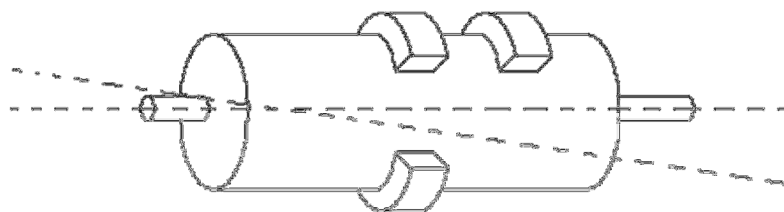
**Figure 2-3** Static Imbalance

- **Couple Imbalance:** As detailed by Figure 2-4, couple imbalance is represented by two imbalance masses separated by  $180^\circ$  from each other. This type of imbalance is often the result of incorrect balancing attempts on a static imbalance. Couple imbalance is identified by detecting the same magnitude of vibration at each end of the shaft; however one end will be  $180^\circ$  out of phase with the other.



**Figure 2-4** Couple Imbalance

- **Quasi-Static Imbalance:** As detailed in Figure 2-5, this can be viewed as a combination of a static and a couple imbalance. This will produce different amplitudes of vibration; however the phase difference will still be  $180^\circ$ .

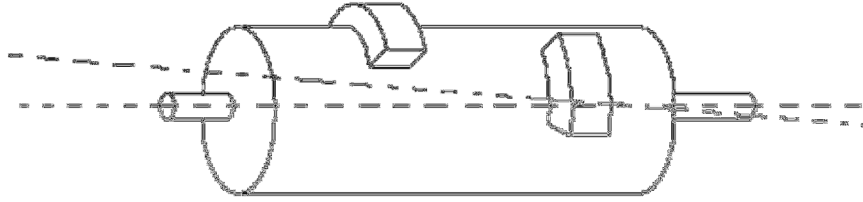


**Figure 2-5** Quasi-Static Imbalance

- **Dynamic Imbalance:** This is the most common type of imbalance found in industry. As can be seen by Figure 2-6, it is characterised by additional masses which lie in a configuration not described by static or couple imbalance. Dynamic imbalance can be detected by discovering a



difference in both the amplitude and phase of vibration (the vibration will not be 180° out of phase).



**Figure 2-6** Dynamic Imbalance

Imbalance may occur in a single plane or, more commonly, multiple planes. To add further complication, imbalance can also be a function of other underlying 'root causes'. Thus imbalance can be caused by a misalignment, looseness, shaft/thermal bow amongst others. This variety of potential causes has resulted in a wide range of work on the subject, which is still on-going.

#### **2.3.1.1 Diagnosing Imbalance**

An extensive guide to traditional and industry-standard methods of diagnosing an imbalance can be found by several authors. This includes Bently, (2002), Muszynska, (2005) and McMillan, (2004). Typically, increased, steady 1X vibration indicating imbalance is then supplemented by additional studies ruling out the presence of underlying faults. Increased vibration not only at 1X but at other points in the spectrum can be indicative of other faults within the system.

Examples of the on-going work in this area include Villa *et al.*, (2011), where the authors studied diagnosis of imbalance and misalignment detection under a wide range of operating conditions. This study focuses on a statistical analysis approach, of which the authors report high accuracy of diagnosis across large speed and load variations. The authors discuss the main limitation of the system as an inability to determine the severity of the fault.

Sinha, (2013) deals with a different aspect of diagnosis. In this case, 'fan blade off' conditions are considered, causing a huge imbalance within a system. In this case the author considers diagnosis of the secondary issues occurring from the imbalance – including rotor/stator rub. Consideration is given for dynamic

forces within the system, and through the analysis of such an event a better understanding such a potentially dangerous situation can be achieved.

Wang *et al.*, (2012) discuss the consideration of gyroscopic effects in fault detection and isolation. In this case, continuously distributed imbalances have been considered – as caused in such cases as a build-up of deposits through a machine. Through a combination of approaches in describing the gyroscopic effect, a high level of accuracy for fault detection has been determined by the authors.

Less conventional techniques for determining imbalance have also recently been developed. One example is Li and Chen, (2011), where the authors propose an intelligent diagnosis method using a combination of wavelet transform and ‘ant colony optimisation’. Real plant data has been used for feature identification, whereupon a clustering approach is used for assessment of these features in the frequency domain.

These examples demonstrate the on-going nature of research into diagnosing imbalance, alongside the different potential causes and issues that arise from this complex fault.

### **2.3.1.2 Imbalance Root Cause Analysis**

In addition to imbalance as an individual fault, a number of researchers are concentrating on increasingly long fault chains in rotating machines. Understanding if imbalance is a function of another fault can be of high importance, as in these cases correcting the imbalance will not fix the machine in question and as such the underlying fault can pass unnoticed.

A common combination of rotordynamic faults is imbalance and misalignment. Many examples of work investigating the links between these exist. One recent example of interest is that by Rameshkumar *et al.*, (2011), where the coast down times for various combinations of fault have been studied. The authors found measurable differences for the combinations studied, indicating a method of differentiating the two faults. It is worth noting however that the severity of the

faults studied was quite high, and in most cases it is desirable to determine the nature of a fault before machine shutdown due to excess vibrations is required.

El-Shafei *et al.*, (2007) details a study into oil whirl under different cases of imbalance and misalignment. The effects of the fault combinations on the onset of whip/whirl phenomena have been assessed, with an emphasis on determining the onset of instabilities. Such complex combinations of faults are beginning to be studied in more detail, as the effects of individual faults are beginning to be understood in greater detail, and research emphasis shifts towards systems which contain more broad capabilities.

Lal and Tiwari, (2012) describe a new development of a fault identification algorithm. In this case, various imbalances and misalignments have been detected and classified through a least-squares approach to classify forced response measurements. This case uses run-up and run-down data in order to determine the fault in question. Such combinations of established techniques provide another aspect to current research in this area.

One further example of this area of research is Didier *et al.*, (2012). In this the authors study the quantification of nonlinear effects in order to differentiate a number of rotordynamic faults, including imbalance. A complex system involving harmonic balance methods has been refined in order to differentiate a number of faults within a system. The advancing ability to model and predict nonlinear effects is providing a rich area of research in the area of fault diagnosis in rotating machinery.

### **2.3.1.3 Classifying Imbalance**

For a next generation IVHM system, it is necessary for automated fault classification to be integrated. Once a method of diagnosing imbalance and determining the root case has been developed, the use of AI (Artificial Intelligence) techniques enables a system to be integrated into broader use.

A wide variety of techniques exist for this purpose, which provides the subject of many works of broader scope than this. As such, a few illustrative examples of current developments have been listed.

Samanta and Nataraj, (2008) detail a number of AI techniques including adaptive neuro-fuzzy interface systems, ANNs and generic algorithms. These techniques are assessed for their ability to classify cracked rotors through continuous wavelet transforms or transient response data. The authors find different strengths and weaknesses in each approach.

Another review into AI approaches for fault classification has been conducted by Jayaswal *et al.*, (2010), the authors in the case detail ANNs, fuzzy logic and wavelet transforms. After comparison, the authors designed a hybrid approach to diagnosis which was tested initially on a bearing fault before extension to imbalance. Such hybrid approaches are becoming increasingly popular in order to overcome the limitations of respective systems.

Srinivas *et al.*, (2010) describes a combination of wavelet transform and ANN in order to assess combinations of imbalance and shaft cracks. The authors describe a 99.9% success rate for the tested conditions, indicating the potential accuracy of such techniques. It is worth noting however that the authors in this case chose a very limited range of operation in order to train the ANN, and as such much further development would be required to make such a system viable.

One further example, with particular relevance to this project, is the work by Santos *et al.*, (2009). For this case the authors have applied an ANN in order to predict imbalance correction masses. As part of this, imbalance size and location is determined through a modelling approach incorporating gyroscopic effects and bearing dynamic force coefficients. Whilst this approach does not incorporate experimental testing, it is important to note the potential viability of such approaches to imbalance classification.

These examples demonstrate some current developments in imbalance fault classification. It is clear that such techniques can enable efficient automation of imbalance detection approaches. Despite this, research in this area is on-going, and 'industry standard' approaches have yet to evolve, as each researched approach includes its own set of advantages and disadvantages.

#### **2.3.1.4 Imbalance on Rotordynamic Test Rigs**

Due to the complications and costs involved with seeding faults such as imbalance into complex rotating systems, alternative approaches are commonly involved for experimental studies. One of the most common is the use of lab based test rigs. Such rigs often consist of simple bearing/rotor/stator combinations into which a variety of faults can be seeded. The advantages of these rigs include the ability to easily simulate a wide variety of faults in a lab based environment at relatively low cost. Some examples with relevance to this project have been highlighted as follows.

Ganeriwala *et al.*, (2009) tested a technique for measuring operating deflection shapes (ODS) in order to detect imbalance cases. These studies were conducted on a MFS (of the same model as used throughout this project). It is, however, worth mentioning that data for the experiments in this paper were collected using 14 accelerometers, which are easy to apply to such a simulator, but it may be much more difficult to configure this many sensors on a complex system. Such considerations are often overlooked when rigs such as this are used for studying rotating machinery. Despite this limitation, the paper achieved its stated aim in proving the hypothesis “when an operating machine becomes imbalanced, its ODS will change”.

Saleem *et al.*, (2012) provides another example of imbalance detection and quantification through a simple lab based rig. The standard approach to monitoring 1X vibration is combined with shaft deflection measurements in order to pinpoint the fault. The authors state their intention to include misalignment and looseness into their next generation of study, highlighting one of the current considerations of current researchers.

Such lab based rigs are also commonly used as a vehicle for validating studies. In Bai *et al.*, (2012), a model for predicting subharmonic resonance through a rotor/stator system with a selection of bearing nonlinearities has been validated in this way. The simple experimental rig enables model updating and correction to be performed, from this more complex models can be build which surpass the complexity of lab based rigs.

A Spectraquest MFS has been used in another example of recent research by Widodo *et al.*, (2012). The authors develop a technique for improved maintenance through the use of an ANN, however in this case thermal images have been used alongside vibration information. The intent of the researchers in this case is to propose an alternate method to vibration data for fault diagnosis. Despite examples such as this, vibration data continues to be the most commonly used approach for fault diagnosis in such cases.

#### **2.3.1.5 Simulating Imbalance**

In addition to the experimental results often conducted on lab based rigs, simulation forms an important part of the latest research into imbalance faults. Once again this is a huge area of research, and so for the purposes of illustration a selection of recent work has been described here in order to highlight some key themes and recent trends.

High-fidelity simulations such as FEA provide the ability to model a system in great detail, along with the potential for high accuracy. Studies such as that by Grobler *et al.*, (2011) have used this in order to tackle the problem of imbalance, in which detailed effects such as geometry alterations can be incorporated into the study.

High-fidelity studies have also been performed by Creci *et al.*, (2011), in this case a whole engine model for a gas turbine has been detailed along with included imbalance faults. In order to assess the characteristics of gas turbines before test examples are constructed, finite element models are routinely created. Advantages therefore exist in building the capability to predict imbalance faults into high-fidelity models, as imbalance prediction can then be incorporated into complex systems before experimental data is available.

FEA approaches are also being combined with other methods. Cakmak and Sanliturk, (2011) use a multi-body system model in order to study bearing response to imbalance. The multi-body model is combined with an FEA model of a shaft and disc, with validation again performed against a lab based rig.

In addition to the high-fidelity approaches, reduced order modelling plays a role in the study of imbalance. Shanmugam and Padmanabhan, (2006) use component mode synthesis in order to perform rotordynamic analysis incorporating gyroscopic effects and imbalance prediction. The authors describe the models applicability to aero engine modelling and highlight the possibility of incorporating nonlinearities into the model. It can therefore be summarised that, despite the advantages of the differing approaches to imbalance prediction, a clear synergy is required between experimental data-driven approaches and physics-based simulation. This synergy is clearly highlighted throughout all of the examples detailed here.

#### **2.3.1.6 Localising Imbalance**

As highlighted in the introduction, the ability to not only determine that an imbalance fault has occurred but also its position within a complex system can lead to significant maintenance advantages. Whilst a large body of work exists on imbalance as a whole, only a small number of these studies take into account localising imbalance. Some of the more pertinent examples of research are outlined as follows:

A number of publications by the Swansea University research group have approached the subject of imbalance localisation. In Garvey *et al.*, (2002), the authors describe a system for robust balancing of rotating machines. The system proposed uses a single run down in a balancing machine, with a requirement to accurately understand the distribution of residual imbalance within the rotating machine. In this case, enriched data from a normal balancing run needs to be obtained in order to understand the imbalance distribution. In this work, methods to achieve this enrichment are not described in detail – however the authors suggest the following three methods:

1. “Measuring static (in the rotor frame) strains on the rotor as well as deflections, since this measurement will contain significant contributions from the higher modes. Rigid-body modes do not contribute to straining”
2. “Perturb boundary conditions by fixing auxiliary systems on to the ends of the rotor such that the combined rotor and auxiliary systems have natural

modes very similar (on the rotor) to the distributions of significant residual imbalance”

3. “Assembled rotors provide the information directly, given ‘line-segment’ approximations of the distribution of residual imbalance for each individual rotor component”

Sinha *et al.*, (2004) describes a final evolution of this set of work, in which imbalance is estimated using a single run down and with a considered misalignment. In the proposed system, run-down information is combined with a finite element model of the rotor/bearing system. Modelling errors due to the complexity of the fluid-bearing system results in a variable error, however greater than 5%. Two experimental rigs have been studied, each with vibration data from a dual accelerometer setup. Whilst the main aim of this study involves the imbalance estimation in terms of amplitude and phase, this also considers imbalance localisation. As one of the most comprehensive series of work available, the clear advantage of this approach is the ability to localise imbalance from a single run down, and including misalignment in the analysis. Limitations include the requirement for two accelerometers, one on each bearing housing, along with the need for highly accurate bearing models. Nevertheless, this work can be considered amongst the current state of the art in the field of localising imbalance.

Santos *et al.*, (2009) describe an analytical model combined with an ANN which has been used to predict the position of imbalance masses for the purposes of balancing. In this case the novel use of an ANN enables not only imbalance to be diagnosed, but also for the position of correction masses to be determined. As with the Lees/Friswell/Sinha work, a model is used in conjunction with experimental data for the purposes of correction. The work focuses on the size of correction masses as opposed to localisation, and thus some issues are overlooked. This includes the study of few imbalance types and little consideration for sensor positioning. The authors state that “The procedure presented can be used in turbo machinery... that require(s) continuous



inspections". Despite these constraints, the approach in using an ANN to achieve imbalance prediction provides a relevant aspect to the study.

One recent work which claims to localise imbalance accurately is by Yang and Hsu, (2010), the authors use trending data and reasoning systems to locate imbalance and shaft bow across a system. Quick diagnosis is achieved by avoiding the study of all fault combinations, and the authors claim the ability to localise shaft bow and imbalance in large rotating machines. The techniques rely extensively on previous searches, and are limited to large, stable machines operating at a specific RPM.

Another model-based method utilising experimental correction is detailed by Jalan and Mohanty, (2011). This approach is similar to that detailed by Lees and Friswell, however with expansion to include imbalance, misalignment and cracks. Once again, limitation in modelling accuracy and intrusive sensor requirements are the main system limitations, however the strength of the combined model/correct data approach can be highlighted by the claimed success rates.

Chen *et al.*, (2005) attempt to circumnavigate the requirement for complex bearing models incorporating Reynolds equations. A three disc system is used for the purposes of imbalance localisation. In this case the requirement for Reynolds equations has been removed through the study of bearing housing motions. The study only focuses on a limited range of imbalance, and requires extensive measurement at various speeds in order to operate. However, the authors state that "It is possible, in theory, to identify ... the imbalance state and/or the configuration state provided appropriate journal eccentricities and bearing housing motions are measured over a period at a sufficient number of speeds"

Markert *et al.*, (2001) approached imbalance identification and localisation using a least squares fitting approach. Accurate linear models have been used for the purpose of predicting equivalent loads on the system. Comparisons against vibrational data have enabled the accurate position of the faults to be measured. The authors also considered the effects of a rub on the system,

including noisy signals, short sample lengths and other complications. It was found that accuracy remained high throughout these tests. Despite this, six accelerometers were used to achieve the high accuracy (99.7%). It was found by the authors that reducing the number of sensors to 5 maintained this accuracy, however if only three were used the accuracy dropped to 73.4%, highlighting a limitation of the system.

The work by Sudhakar and Sekhar, (2011) describes a model-based method for fault identification using a minimal sensor suite. This is achieved through the analysis of transverse vibrations at a single location. Throughout the paper, three different approaches are studied – least squares minimisation, equivalent loads minimisation and vibration minimisation. A reduced error is found to occur using a proposed modification to the typical equivalent loads minimisation approach. Whilst this approach uses a single sensor, this results in a large amount of vibration data is required in order to achieve sufficient accuracy. In addition, only imbalance has been studied, and within a limited operating range. Despite this, the potential for a single sensor to accurately localise imbalance can be shown. The described examples show various approaches to imbalance localisation. However, the more detailed examples can be split into broad two categories:

**1: Model + Experimental Correction:** These approaches have advantages in that the requirement for experimental data is minimal. The case of a single run down can be ideal when a severe imbalance is detected, and running any machine with an imbalance fault is undesirable. The trade-off of these approaches is the requirement for highly accurate and detailed models. In addition, claimed success rates appear to be less than the data-driven approaches.

**2: Experimental + Limited Modelling:** In these cases, the requirement for accurate models, and the inaccuracies arising from this are reduced. Developments have also been made into reducing the sensor suites required. However, extensive data collection is still required in many cases and studies which include validation and multiple faults have not been advanced as far as

those in 1. From the examples detailed it can be noted that whilst some researchers have developed systems for imbalance localisation, a system capable of operating in both rigid and flexible regimes using a single sensor and incorporating consideration for underlying faults has yet to be developed. It can be concluded that whilst model-based studies can still benefit from improved accuracy, data-driven approaches require extending and refining in order to make these more applicable for industrial applications. A summary of the state of the art can be seen in Table 2-1.

### **2.3.1.7 Imbalance – Overview**

It can therefore be demonstrated that recent advances have enabled imbalance to be diagnosed through both simulation and data-driven approaches, root causes established, automated classification performed and localisation achieved. Despite this, clear limitations in all approaches exist, and as such a complete system for imbalance estimation and correction has yet to appear.

All of these aspects of imbalance need to combine in order to form part of next generation IVHM systems. From the research conducted here, it can be surmised that there is still room for developments in terms of a system which can diagnose and, in particular, localise imbalance faults by a method which is applicable in industrial situations. In aiming to achieve this, key points to consider include:

- The need for a synergy between data-driven and physics-based simulation approaches.
- The use of a single, non-intrusive sensor which can achieve high precision and accuracy using data-driven approaches would be a major advance on current research.
- Any system capable of localising imbalance should also consider other rotordynamic faults.
- Numerous studies highlighted here provide indications for detailed future work into systems of imbalance diagnosis and localisation.

Method (by Author)	Modelling Requirements	Data Requirements	Comments
Sinha/Friswell/Lees (2004)	Accurate bearing models required, or accurate pedestal movement.	Developed to work with data from a single run-down.	At least two sensors required, works in the flexible regime. Has found implementation in the power generation industry.
Santos (2009)	Detailed analytical modelling required.	Minimal provided highly accurate modelling exists.	System developed for balancing purposes, thus full imbalance localisation potential is unclear.
Jalan/Mohanty (2011)	Highly accurate modelling required, including bearings.	Unclear, however expected to be minimal assuming fully accurate models.	Claimed to include misalignment and crack diagnosis and localisation.
Chen <i>et al</i> (2005)	Minimal, no Reynolds equations for bearings required.	Extensive multiple speed, multiple sensor information required at bearing points.	Designed to overcome modelling limitations through extensive data collection. Multiple sensors required.
Markert <i>et al</i> (2005)	Accurate linear models required.	Small datasets required from a minimum of five accelerometers.	Proven to work in a wide variety of conditions, however requires both accurate models and preferably six sensors.
Sudhaker/Sekhar (2011)	Detailed linear models required.	Large amounts of data required from various speeds at a single key location.	Claimed to work with a single accelerometer, however limited testing performed and required large amounts of data.
Yang/Hsu (2010)	None for system operation.	Large amounts of stored data required for comparison, noise free and steady state.	Aimed at quick diagnosis and localisation, incorporates shaft bow. Large data requirements.

**Table 2-1** State of the Art in Localising Imbalance Faults

### 2.3.2 Other Rotordynamic Faults

It can be seen from the detailed review into imbalance that any future system for diagnosing and localising such faults should take into consideration other common rotordynamic faults. Any efficient imbalance localisation system is required to work in the presence of alternate faults, and be able to establish the root cause of the fault. With this in mind, a study into some state of the art research into other faults has been undertaken. In keeping with the eight common faults highlighted for rotating machinery, the seven to be studied in this section are as follows:

- Misalignment
- Shaft Cracks
- Blade Cracks
- Rotor Bow
- Fluid-Induced Instabilities
- Rub & Looseness
- Bearing Failure

As per the section on imbalance, a number of recent, relevant publications for each fault have been assessed in order to highlight trends in rotordynamics and issues of interest to this project in particular. The papers described also bear relevance to the core study of imbalance localisation in the presence of other faults.

### **2.3.2.1 Misalignment**

This is another common fault which can potentially inflict considerable damage in rotating machines. As with imbalance, misalignment in a whole system can be complicated by secondary faults (e.g. a misalignment which causes a rub). El-Shafei *et al.*, (2010) is an example of the on-going research in this area, in this case a unique combination of angular misalignment and oil whip/whirl is detailed. The authors describe how small degrees of misalignment can be utilised in order to prevent the onset of fluid induced instabilities, tested through the use of a lab based test rig. Such research presents a new dimension in looking at common rotordynamic faults, with aspects that could be applied to future design for IVHM systems.

Bahaloo *et al.*, (2009) demonstrate interesting research into misalignment from the perspective of physics-based simulation. The authors construct mathematical models of a simple rotor system with a misaligned coupling and collect harmonic response data from this to assess the severity of different misalignment cases. Such models are useful throughout the life of rotating machines – from design to implementation, although again successful validation with experimentally obtained data is key. The authors highlight the fact that although misalignment is a prevalent and serious fault, no comprehensive

research has been performed for treating this problem. The methodology applied includes deriving the energy expressions applying the Ritz series method, constructing the equations of motion and then using the harmonic balance method to look for multi-harmonic responses. The paper demonstrates the on-going research to understand and model the fundamentals of such faults, in order that improved diagnosis and prognosis methods can be built upon such knowledge.

As with imbalance, localisation and prognosis of misalignment is a complex topic to research. Studies such as Bahaloo *et al.*, (2009) can make accurate predictions for misalignment in a simple system with one coupling. However, real systems (e.g. aircraft gas turbines) have several potential locations of misalignment. This is an area where few researchers have made an impact. Remaining useful life predictions for misalignment are complicated for the same reasons as with imbalance. Villa *et al.*, (2011) discuss statistical diagnosis of misalignment faults, with reference to prognosis. The authors use the example of a wind turbine for their studies, but stress the applicability to other systems. Differentiation with imbalance faults is also covered (as these two faults are closely linked). Unlike the work by Bahaloo *et al.*, (2009), emphasis is given to the machine in question operating over a wide range of operating speeds and conditions. This is achieved through the use of an angular resampling method. Prognosis is tackled through the use of a statistical diagnosis algorithm based on the significance level of the faults in question.

### **2.3.2.2 Rub & Looseness**

Rub is always a secondary fault (i.e. a product of another fault such as looseness) and can lead to fatigue and wear. Rub and looseness can create complex vibration signals which are difficult to diagnose using traditional methods. Modelling and simulation of rub and looseness faults have been considered in several recent works.

This includes Ngolah *et al.*, (2011), which details the monitoring and diagnosis of common faults (including rub and looseness) based upon a three layer Artificial Neural Network (ANN). A series of 10 key performance indicators were

identified and used as training. The authors test the system in a lab environment, but stress the applicability to industrial applications. The research indicates one of the latest methods of research which enables the implementation of diagnosis techniques. It is a useful tool for rub and looseness studies, as it incorporates a variety of faults which could 'underlie' such a fault. Despite this, the research relies on clear features for each fault, which can be much easier to identify in a lab environment as opposed to 'noisy' industrial applications.

Lu *et al.*, (2007) have performed several studies into rub and looseness, including this example in which a flexibly mounted shaft has an induced rub due to a range of contact rings. The study focuses on the potentially dangerous effects of rub in causing excessive non synchronous and chaotic vibrations. The links with imbalance and misalignment are discussed and detailed. The considerations for real world cases in the described research are considerable, as part of the drive towards full understanding of the nonlinear effects of rub and looseness.

Localisation of rub and looseness across whole systems is relatively lightly studied in literature. Many works (including those already cited) look at single or dual-rotor systems where localisation of such faults is not an issue. In an industrial setting, complex systems may comprise many rotors in several compressor and turbine stages, significantly complicating diagnosis of such faults. Current research into prognosis of rotor-stator rubs lies mostly within the domain of data-driven techniques. Modelling and simulation research can be used to support data-driven techniques for prognosis and condition-based monitoring. Han *et al.*, (2008) is an example of this; the authors use finite element modelling to construct a dual rotor model. Various types of rub-impact are then studied.

Such studies can provide a wide range of information, which can then be combined with data obtained from live systems, potentially with seeded faults, in order to construct accurate remaining useful life predictions. As pointed out by the authors, one key advantage of simulation is the ability to study more

complex systems with a higher number of rotors, which is used throughout this research. This presents a different approach to identifying features for identification of rub and looseness.

### **2.3.2.3 Fluid Induced Instabilities**

Fluid-induced instabilities (often referred to as whip and whirl) are potentially very serious faults which can result in wear, fatigue and extensive damage to machine components. Such instabilities can be found in interstage seals, fluid lubricated bearings and blade-tip clearances. Research into simulating and modelling fluid-induced instability has produced several works of interest to fault diagnosis of rotating machines in the last few years. de Castro *et al.*, (2008) is a good example, where nonlinear mathematical models are prepared for a rotor-bearing system. The models are then used to predict instability thresholds. The authors consider a test case against a power plant turbine and a test rig, therefore validating the simulations. The case of imbalance faults causing whip and whirl phenomena is also considered. The main conclusion therefore drawn from the work is that the authors nonlinear hydrodynamic journal bearing models enable sufficiently accurate simulations for predicting instability thresholds.

Fan *et al.*, (2011) represents an example of work from the perspective of aero engine turbines. In this case, start-up conditions are studied using a full Hilbert spectrum. The aim behind the paper is to accurately predict the point at which whip and whirl occur, thus enabling this to be avoided at the design stage. Such findings could potentially also be used to identify whip and whirl as the case of a fault after a period of wear in the operating machine.

Prognosing fluid-induced instability is a relatively lightly researched topic. Fluid instabilities can be covered as part of extensive research into remaining useful life of bearings. The potential exists for modelling and simulation techniques such as those detailed above to become a part of prognosis for fluid-induced instabilities due to the fact that it can be very difficult to seed such faults into live systems for testing and evaluation. As with other faults detailed in this report, many studies have been performed with the aim of describing fluid-induced



instabilities based on the measurement or simulation of single (or occasionally dual) rotor setups. Physics-based simulation with the aim of localising fluid instability faults across a whole system can be limited by the complexity of both the fault and the system, hence, the simplification to single rotor-stator bearing systems.

#### **2.3.2.4 Bearing Failure**

An area where data-driven techniques are still providing the basis of much research in the field of rotordynamics is that of bearing failure. The title ‘bearing failure’ can cover a wide range of potential issues which continue to be studied in detail. Faults can occur in all kinds of engine bearings – the inner and outer case, the cage and the rolling elements, fluid induced instabilities (addressed in a separate section), lubrication and the complexities of active magnetic bearings to name some examples. All types of bearing relevant to rotating machinery are the subject of on-going research, and this subject has the potential to form several separate papers. As a brief highlight, some recent examples are discussed as follows.

Data-driven techniques have enabled accurate bearing diagnostics and prognostics to be described for a range of rotordynamic systems. Despite the prevalence of data-driven research in this area, research from a physics-based simulation perspective has also recently produced some interesting papers of relevance to condition monitoring and health management of rotating machinery.

This includes Kappaganthu *et al.*, (2010), in which rolling element bearings have been studied through the use of nonlinear models. The included nonlinearity in this case is clearance, and the model is then used in order to study chaotic motions, in particular the regions of chaotic response. The research forms part of an on-going drive to develop an accurate model-based diagnostic technique for rolling element bearings, taking into account clearance nonlinearities and chaotic responses.

Gupta *et al.*, (2011) demonstrate another example of the latest research into instability and chaos in rolling element bearings through high-fidelity simulations. This detailed and complex study involves the application of a novel scheme to analyse the quasiperiodic response of the system combined with a nonautonomous ‘shooting’ method. This work highlights the level of detail to which nonlinearities and complex nonlinear motions in bearings are beginning to be understood and accurately modelled. Again, such work presents the potential for design for IVHM in future evolutions of the research.

As so much research has been performed (and is on-going) into bearing faults across a wide variety of mechanical systems, both prognostics and localisation of bearing faults have been researched in somewhat more detail than some of the other faults detailed here. Despite this, much work still needs to be performed in order to translate some of this core research into industrial applications. Research such as that detailed above has made significant advances into determining bearing failure as the root cause of a malfunction. Detecting which bearing is failing across a complex system has received somewhat less research.

Bearing prognostics is another area with much on-going research being performed – both in the simulation and data-driven domains. To give an example, Hong *et al.*, (2009) combined grade life and extensive mathematical modelling techniques in order to produce prognostic models for aero engine bearings. The results are described by the authors as ‘practical and verifiable’. Although a number of similar recent studies exist, this work is of note for the extent of the studies performed which include bearing test stand run-to-failure validation. The lab results appear impressive, this research has yet to be applied and tested in real life applications – indicating that despite the number of parameters considered, it is still not possible to sufficiently model naturally occurring phenomena sufficiently.

A large body of work in this area also exists from Borghesani *et al.*, (2012), where several examples of data-driven techniques can be seen applied to a wide variety of bearing types. An example of recent developments involves the

use of ‘cepstrum pre-whitening’ in order to remove sufficient noise for accurate bearing diagnosis and prognosis. This work is particularly noteworthy due to the emphasis on real world applications, where the traditional lab based techniques of order tracking and synchronous averaging do not provide sufficient noise removal for harsh industrial environments. The addition of such techniques is a crucial step in developing the current generation of diagnosis and prognosis algorithms for use in future IVHM systems.

#### **2.3.2.5 Shaft Cracks**

Another potentially serious fault in rotating machinery is shaft cracks, and so early detection of any such fault is highly important. Methods of crack formation and propagation can be diverse, and range from high and low-cycle fatigue to stress corrosion. Simulation and modelling of shaft cracks can have significant advantages over data-driven methods. Perhaps the most obvious advantage is the relative simplicity of inserting a fault into, for example, a finite element model as opposed to seeding a fault in a working industrial machine. As such, research into shaft cracks has been progressing steadily with the corresponding increases in computing power.

A clear synergy between data-driven and physics-based simulation research can be implied by a number of recent works of research. An example of recent advances from a data collection perspective is Li *et al.*, (2010b), which details statistical models based on historical data for condition monitoring purposes. This unique work uses the human auditory system as inspiration for enriching methods of mechanical faults and features extraction. The results indicated by the paper are perhaps not as convincing as some other methods discussed in this paper, it describes an interesting ‘outside the box’ method of tackling common problems.

From a modelling perspective, Bachschmid *et al.*, (2011) cover a wide range of vibration phenomena in order to develop a model-based identification and severity procedure. This work is noted for its thoroughness in modelling procedure, including accurate modelling of the crack breathing mechanism. A combination of high and low-fidelity models are validated through experimental

study and ‘excellent’ accuracy is claimed by the authors in detecting crack position and depth through the use of the proposed model-based diagnostics.

The nature of shaft cracks has resulted in a wide variety of research being performed into both the localisation and prognostics of these faults (indeed, the two topics can be considered related). Recent examples of work in this area include Karthikeyan *et al.*, (2008), which details crack localisation using forced response modelling. In this case, a test rig was constructed consisting of a circular shaft supported by two bearings. Frequency-domain data was used to create a localisation algorithm, designed in combination with an FE model. Although this research provides accurate localisation in a lab environment, it remains untested in a more complex system (e.g. a full gas turbine).

Inoue *et al.*, (2010) describe finite element modelling of crack propagation, with validation against experimental results provided to demonstrate the validity of such modelling techniques. The paper concentrates on natural frequencies and resonance curves. Whilst the authors claim improvements in the ability to understand such faults, again the system in question is quite simple and such FEA models are difficult to scale up to full size applications.

#### **2.3.2.6 Blade Cracks**

Blade cracks, if allowed to develop, can result in serious consequences. Cracks can form due to high centrifugal stresses across operational cycles (in the case of an aircraft gas turbine, for example, start up and take off through landing and taxi). As excessive crack growth can lead to catastrophic rotor/blade failure, early detection and prognosis of such faults are essential. As with shaft cracks, physics-driven simulation of blade cracks is an area of significant research. This varies from high-fidelity finite element models to low-fidelity system and mathematical models. The recent work demonstrated by Green and Casey, (2005) is a good example of recent mathematical modelling from a diagnostic perspective. In this paper the authors concentrate on early detection using global and local asymmetry crack models. 2X harmonic components are identified as key areas for the early detection of blade cracks, however again

this paper suffers from being applied and tested on a relatively simple system which may not scale up to a full size turbine.

Inoue *et al.*, (2010) demonstrated high-fidelity modelling, the authors used FEA to model crack growth, making comparisons and validating against an experimental rig. This work is particularly interesting as it outlines the advantages and drawbacks with the latest state-of-the-art modelling techniques.

Localisation and prognosis of blade cracks have also benefitted from recent advances in simulation and modelling. Sawicki *et al.*, (2008) contains details of work on a novel active magnetic bearing system for use in the early detection, localisation and prognosis of blade cracks. Again the emphasis is on early detection, with the bearings used to excite the system in order to obtain optimum response vibrations for analysis. The authors admit the approach has some merit in diagnosing blade cracks, however it is in the early stages of development and work is on-going. FEA has also been used extensively to support blade crack prognostic tools; Xiang *et al.*, (2007) is an extensive example of recent work. In this case, a number of advanced FEA methods are applied to produce accurate FEA solutions – these include surface-fitting techniques and the contour-plotting method. The authors experimentally validate their work and suggest that it can be applied to prognosis and quantitative diagnosis of blade cracks. Despite the claimed advances, again the scalability of such research to full size turbines is an issue – particularly with regards to the complexity of the FEA models.

#### **2.3.2.7 Rotor Bow**

Rotor bows can be a primary source of unwanted vibration in gas turbines. The main cause of a rotor bow (rotor bows do not include bows due to gravity) are thermal differences in a system caused by operating conditions. It is noted by Domes, (2008) that this non-symmetrical thermal distribution can cause excessive imbalance to the extent where a gas turbine will not start correctly. Such rotor bows are common on start up or shut down, and are often accounted for in operational procedures. However, if thermal ‘hot spots’ exceed a given tolerance level, they can cause permanent imbalances due to rotor deflections.

Such rotor bows can lead to other faults, including rubbing and looseness which complicate isolation and localisation.

Traditional data-driven techniques for detecting rotor bows involve combinations of slow roll and vibration data Maalouf, (2007). More recently, mathematical modelling techniques such as that detailed by Jim *et al.*, (2008) have been used in order to diagnose residual rotor bows, and differentiate these faults from other sources of imbalance. The authors of this paper build upon established methods for the models, and are unique in that they concentrate on response at the bearing points.

The recent work that exists on attempting to localise rotor bows across complex systems tends to be data-driven in nature; see Galka and Tabaszewski, (2010) where the authors used statistical symptoms based on known data as a method of diagnosing and prognosing a number of faults, including rotor bows and imbalance. This paper attempts to address the irregularities and fluctuations that occur over a long service life. In order to achieve this, a modified energy processor model is created, using data drawn from large steam turbines over long periods of life.

Prognosing rotor bows is a complex subject. As rotor bows are often caused by temperature deflections, making predictions for remaining useful life and potential future problems lies not only in the realm of mechanical rotordynamics but also to some extent in thermodynamics. The recent work detailed by Sinha, (2009) is of note for detailing diagnosis and quantification of various rotordynamic faults and describing the advantages of mathematical modelling over traditional vibration-based approaches. The topic of scalability regarding FEA models is discussed, including an argument for the use of partial (simplified) mathematical models for large, complex systems.

Another two works which are of interest with regard to modelling of rotor bows include Shen *et al.*, (2008), where the authors modelled a rotor-bearing system with a permanent rotor bow, looking at the impact of secondary faults such as rub. The study of fault combinations in this paper is useful for fault differentiation studies; however the authors study a permanent, initial rotor bow. This therefore

does not take into account developing or worsening faults and the different vibration phenomena that are observed as such faults are develop. Lees *et al.*, (2009) describe the importance of model-based fault identification techniques and outlines recent research in the area, providing a good reference paper for more research on this specific fault.

### 2.3.2.8 Summary Table

Although a number of recent and relevant works have been described within this review, it is important to acknowledge additional publications which have been studied in order to provide ‘building blocks’ for this project. To this end, the following table has been created. The table by no means details all relevant methods and approaches currently being investigated – however it details themes which were found to be common across many areas of current research. It is intended for the detailed table to compliment the important works described in more detail in the previous section of the paper, separated by fault type. This can be seen in Table 2-2.

Faults	Sensors	Fault Identification Techniques	Localisation of Fault	Prognosis	Work of Note in Fault Modelling
Imbalance	Accelerometer Velocity Transducer Proximity Transducer	Operating Deflection Shapes Time-Frequency Analysis & Many Others	Neural-Network Modelling and Time-Frequency Analysis	FCM-Markov Model	Unbalance in Full-Engine FEA Model, Early detection in aero engines
High Radial Loads & Misalignment	Accelerometer Thermocouple Displacement Transducer Angular Sensor	Bearing Temperature Observation Advanced Software-Driven filtering methods	Various Vibration Analysis Techniques	Prognostic Modelling Using Simulated Vibration Data	Modelling the relationship between Misalignment and other faults Harmonic Balance Method
Rub & Looseness	Accelerometer Velocity Transducer Optical Sensor	Single Value Decomposition Time-Frequency Analysis	Least-squares fitting approach	Adaptive Wavelet de-noising for Prognostics	Rub & Looseness using FEA models Whole engine modelling techniques
Fluid Induced Instability	Proximity Probes Keyphase Transducer	Full Spectrum Plots Large Amplitude Subsynchronous Vibration Detection	Blade Tip Clearance and Loading Distribution	Cross-coupled stiffness and direct-damping studies	Nonlinear Modelling Accuracy of Model Based Diagnostics Numerical Modelling
Bearing Failure	Displacement Transducer Proximity Probes	Post-failure analysis for future failure diagnosis Dynamic time-frequency analysis	Statistical Change in the Bi-Spectral Domain	Numerical modelling of aero-engine bearings Model-based prediction of remaining useful life On-board prognostics	High and Low Fidelity Dynamic System Modelling Comparisons of algorithms to understand bearing vibration phenomena
Shaft Cracks	Keyphase Transducer Proximity Probes	Higher Order Spectra Neural Networks Grid Support Vectors	Forced Response Measurements	Non-intrusive torsion vibration monitoring	Statistical Analysis FEA Modelling
Blade Cracks	Keyphase Transducer Proximity Probes	Hilbert-Huang Transformation Model-Based Diagnostics Morlet Wavelet/Quantum Techniques	Novel Bearing Structures	Active Magnetic Actuator	Global and Local Asymmetry Modelling Finite Element Modelling
Rotor Bow	Keyphase Transducer Proximity Probes Seismic Transducer	Examination of ‘Slow Roll’ data Model-Based Diagnostics	Partial Mathematical Modelling	Statistical Symptoms Analysis	Advantages of Fault Modelling for Identification Nonlinear Modelling Techniques

**Table 2-2** Rotordynamic Fault ‘Summary’ Table

### **2.3.2.9 Rotordynamic Fault Summary**

This section has reviewed some of the latest research around a number of rotordynamic faults – namely imbalance, misalignment, rub and looseness, fluid-induced instability, bearing faults, shaft cracks, blade cracks and rotor bow. Each fault was reviewed from the perspective of sensors, diagnosis, prognosis, localisation and modelling.

Key examples of recent work into the eight described faults have been detailed through works by a number of eminent authors. Additional work has been summarised and formatted for easy reference. Some current trends amongst the recent body of work include developments in the vast area of modelling nonlinearities, combinations of high and low-fidelity modelling and synergy between data-driven and physics-based simulation approaches.

Despite the large volume of promising research reviewed, further development in a number of areas is required in order to produce effective next generation IVHM systems. In particular, room for development has been identified in the field of localising imbalance through a practical system which includes consideration of multiple faults and operates with a limited sensor suite.

## **2.4 IVHM and Rotordynamics**

Through the study of the aforementioned topics, it is useful to place the research conducted in this review into context with regards to real-world applications. Further to this, it is intended to identify potential areas where more research is required in order to push some of the recent technologies highlighted for this study into industry.

### **2.4.1 The Present Situation**

The bulk of current research into rotordynamics from the point of view of prognostic health management (PHM) can be roughly divided into two types: initial single-fault diagnosis/prognosis techniques and studies into the general requirements and limitations of current systems along with current and future trends. An example of the latter is Pusey, (2007) who provides a good summary



overview of current diagnosis and prognosis techniques with regard to condition-based maintenance.

As a result of this split, a clear gap exists between the core research being performed into rotordynamics from a condition-based maintenance perspective and the identified needs of industry. Taking a fledgling piece of research and applying it to a commercially-ready system (e.g. a gas turbine engine for an aircraft) is a long and complex task. It is nevertheless worth noting that technologies for automatically detecting an imbalance or misalignment in a gas turbine were developed over 10 years before the latest commercial aircraft were conceptualised, and yet these aircraft are still limited in this capacity. This highlights the need for work which links the fundamental research into individual fault diagnosis to 'live systems' for use in industry.

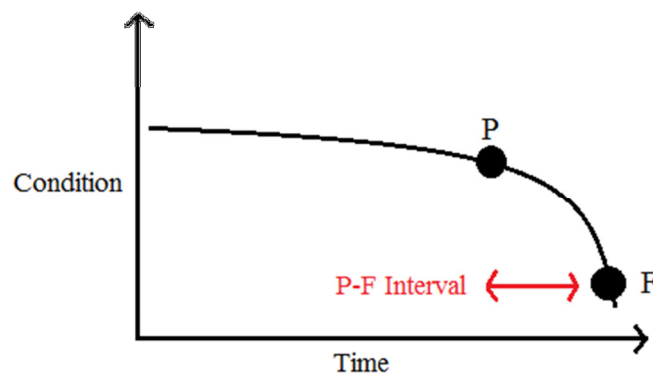
Physics-based simulation and modelling of rotordynamic parts is a well-researched field. Such modelling has been used as the basis of diagnosis and prognosis of faults by many researchers and several recent examples have been outlined in this paper. Occasional studies have been undertaken into modelling multiple faults, such as Jain and Kundra, (2004) who use a system model for online identification of imbalance and cracks. Beyond this, however, very limited research exists. The demands of PHM techniques in industry are such that any system must not only be capable of detecting multiple faults, but must also be capable of detecting these faults across a range of different systems. Other considerations include the afore-mentioned ability to differentiate between multiple faults. Processing also needs to be taken into account, as the objective of these systems is to implement efficient condition monitoring and condition-based maintenance procedures. If processing data is a long, power-hungry process, then this aim cannot be achieved.

#### **2.4.2 The Benefits of IVHM Systems for Rotating Machinery**

The potential impact of accurate fault diagnosis and localisation systems in industrial applications is significant. As noted, Andresen, (2006) states that as much as 44% of on-aircraft maintenance time (90% of total maintenance operations) is consumed with inspection alone. Some of the techniques

addressed in this review enable the maintenance to be more informed and targeted, with inventory ready when needed, providing a significant contribution to reducing maintenance time and cost.

On common method of quantifying the benefit obtained from an IVHM system is through study of a P-F curve. The curve displays the behaviour of a component of system as it begins to fail over time, as can be seen in Figure 2-7.



**Figure 2-7 P-F Curve**

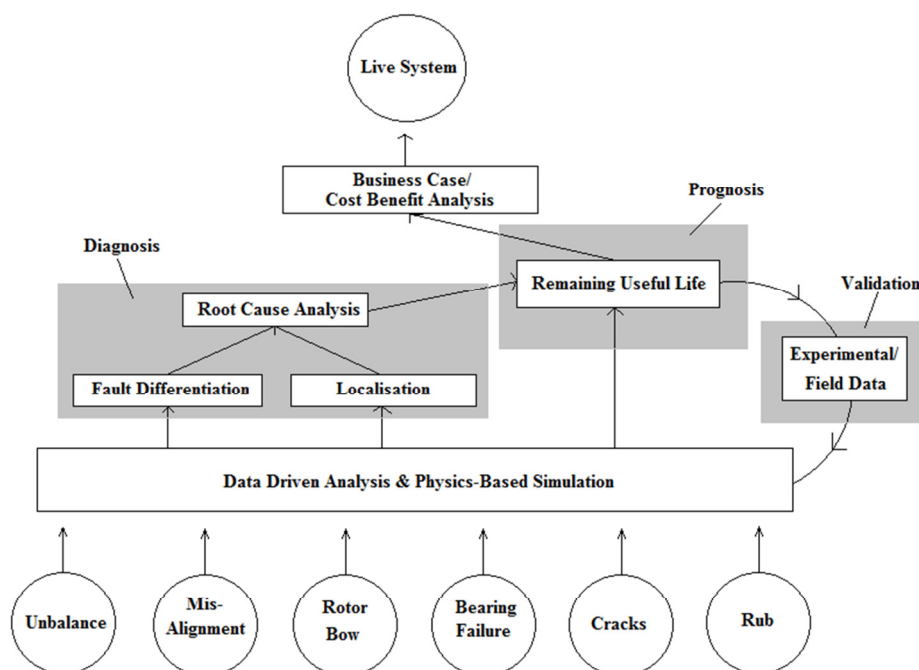
In this curve the point 'P' refers to the earliest point at which a fault can be detected. Point 'F' indicates the point of failure and as such the 'P-F' interval' can be seen to indicate the time range between these points. In the case of diagnosing faults in rotating machinery, the ability to increase the P-F Interval provides obvious benefits, and more importantly, the aim of the diagnosis system is to detect a fault as close to the point 'P' as possible. A comprehensive overview of the role of the P-F Curve and the surrounding implications can be found in the works of Heng *et al.*, (2009).

### **2.4.3 Metrics**

Although quantifying the success of the research studied is difficult, it is possible to define the key areas in which a technique must excel in order to be considered viable. The work by Wheeler *et al.*, (2009) discusses in detail metrics for diagnostic and prognostic analysis, as does that by Vachtsevanos, (2003) and Saxena *et al.*, (2008). The conclusions drawn from these papers

and applied in practice to research like that covered by this thesis indicate that the following metrics are important when considering the potential of a given technique to diagnose faults: coverage, false positive rate and false negative rate. In the case of prognosis, probabilities and lead time to failure are other important considerations. These criteria enable research to be assessed in terms of its suitability for industrial applications. Unfortunately, information on these metrics is not made readily available by the authors of most papers.

Figure 2-8 details a potential framework required in order to push core research, such as that detailed in this report, towards industrial applications. Many studies now exist on individual rotordynamic faults across a wide range of conditions and applications. Some studies have taken this further, with advanced prognostic models and diagnosis of dual faults (primary cause and secondary effect). Future research in the area of rotordynamics from a PHM perspective could potentially provide the bridge between these studies and live systems, by combining physics-based simulations with data-driven techniques and validation against experimental data



**Figure 2-8** Physics-Based Simulation – From Research to Industry

#### **2.4.4 Standards**

Although, as mentioned, an established and commonly applied set of procedures and standards for IVHM has not yet emerged, with regards to rotating machinery a number of standards and procedures can be referred to for detailing and quantifying the faults. These include such aspects as covered by ISO 2953:1999, which details correct balancing procedures and levels of mechanical vibration. Another example would be in the UK Ministry of Defence - Military Aviation Authority (2010), JAP 100A-01 - Military aviation engineering policy and regulation, where mention is made of procedures for debris and vibration monitoring. This indicates a gradual move towards common ground for procedures and standards for IVHM systems. Despite this, research remains varied, and separating the research with potential for moving beyond the lab-based environment into industry can be difficult to identify at first glance.

### **2.5 Chapter Discussion**

This review chapter highlights a number of important topics relevant to the overall project. In this section, trends and conclusions based upon the research performed are discussed.

#### **2.5.1 State of the Art Summary**

In terms of evaluating the effectiveness of the research discussed in this chapter, there are difficulties in identifying a specific technique over others for general application. Most papers reviewed for this research (not just those referenced and discussed in detail) take a technique (new or evolved), validate for a given, specific system and report the success of the research. Despite this, some conclusions can be drawn from assessing common techniques applied across different studies and different faults. Although it is not possible to define the most common methods for diagnosing and prognosing faults in terms of numbers (as it was not possible to cover all recent rotordynamics research for this thesis), the author has identified that the following techniques have featured prominently in the reviewed research:

- **Sensors:** Accelerometers
- **Theoretical Studies:** Mathematical Modelling
- **Physics-Based Simulation:** FEA
- **Data-Driven:** Frequency Domain Analysis
- **Reasoning:** Neural Networking

These techniques appear to be among the most promising currently under development, as they tend to feature numerous times amongst some of the work with wider scope, across fault types and with the most comprehensive validation. There are of course many subsections to these techniques; however it shows one general direction of research and the clear possibilities posed in these areas.

Future developments in the field of IVHM for rotating machinery may incorporate these techniques alongside extensive use of nonlinear modelling and multiple fault interactions. The field of design for IVHM has only recently emerged, however the potential exists for specific nonlinearities to be designed into a system in order to enable accurate diagnosis and prognosis of faults. The development of current algorithms to include diagnosis, localisation and prognosis of a range of faults will provide a significant advancement for future generations of IVHM systems. This combined with cost-effective sensor suites indicates the potential for evolutions of some of the research detailed here to form part of next generation IVHM suites for rotating machinery.

### **2.5.2 Justification for Further Studies in Localising Imbalance**

The eight common rotordynamic faults studied are all of great interest to the rotating machinery research community. However, the fault of imbalance has consistently been referred to as the most commonly occurring. Whilst a vast amount of literature has been produced into the topic of diagnosing imbalance, relatively few of those works consider the localisation of the fault. As highlighted, knowing the position of a fault within a complex rotating machine has the potential to significantly aid maintenance procedures.

Existing published literature in localising imbalance generally falls into two categories: Model-based (with data-driven model updating) and Data-driven. Model-based approaches appear to be limited by the requirement for highly

accurate and detailed models, operating at the limit of current knowledge. Data-driven approaches typically claim higher success rates, however these often use complex sensor suites and large amounts of data to achieve this.

It can therefore be concluded that a system capable of diagnosing and localising imbalance under a wide range of conditions, incorporating consideration for underlying (or secondary) faults, capable of operating in both rigid and flexible regimes and using data obtained using a single sensor represents a clear contribution to knowledge. Not only this, but such a system may possess important industrial relevance.

A number of other points have been highlighted in this review and must be taken into account, and therefore such a system should consider the following requirements:

- Synergy between physics-based and data-driven approaches.
- Nonlinear features may provide clues for improved accuracy.
- Imbalance should be considered in the presence of other faults (root cause diagnosis).
- Such a system needs to automatically classify the imbalance type and location to a high degree of accuracy (>99%).
- The system should be adaptable, and form part of a methodology applicable to a wide range of rotating machines.
- Implementation in next-generation IVHM systems should be considered.

## **2.6 Chapter Conclusions**

Throughout this chapter, a study into state of the art diagnosis, prognosis and localisation of rotordynamic faults from the perspective of future IVHM systems has been performed. Based upon the latest research, imbalance faults have been identified as the most common, potentially serious fault which occurs in a wide range of rotating machines. Whilst a large number of systems for diagnosing imbalance have been discovered, systems which also localise these faults are relatively few in number, and all of those existing experience limitations.

The current state of the art imbalance localisation systems can be seen to rely on a minimum of two sensors, whereas wide ranges of rotating machinery (including a large number of operational aircraft engines) only possess a single sensor. Many current state of the art systems are also limited to flexible operating conditions, with little ability to operate in sub-critical regimes. It can be noted that the only systems attempting to tackle these limitations through a data-driven approach require large amounts of steady state data, with no current consideration of underlying faults. Overall consideration for implementation into an IVHM system for rotating machinery is also lacking. This highlights an important area of Rotordynamics & IVHM which could benefit from further studies. In summary, the following chapter aims have been met:

- A study of key knowledge and current state of the art has been undertaken to aid the work performed throughout this project.
- A comprehensive review of current state of the art in diagnosing, localising and prognosing common rotordynamic faults has been performed and published (see Appendix A and B).
- The requirement for a new methodology for the localisation of imbalance faults in rotating machinery has been highlighted.

The research questions arising from the review of literature can therefore be summarised as follows:

#### **Research Questions:**

- Can a novel system capable of accurately localising imbalance faults in rotating machinery be developed, relying on a minimal, non-intrusive sensor suite and capable of operating under a wide range of conditions?
- How can a synergy between physics-based simulation and data-driven approaches aid imbalance localisation?
- Can imbalance localisation be accurately performed when additional faults exist within the system?
- Is it possible to create a general methodology for imbalance localisation, taking into account potential application in next generation IVHM systems?

## **3 Research Methodology**

### **3.1 Chapter Introduction**

This short chapter is intended to outline, explain and justify the research method to be undertaken throughout this thesis. Many papers were studied and several important findings were identified during the review of literature, and in this chapter these findings have been consolidated into a work outline and structure for researching the localisation of imbalance faults in rotating machinery. In this way, the research questions proposed can be tackled.

As such, the objective of this chapter is as follows:

- Develop a methodology for research into novel means of localising imbalance in rotating machinery.

### **3.2 Structuring the Research**

The research questions proposed encompass a very broad selection of potential avenues for investigation. It is therefore important to consider the points raised from the review of literature in order to structure the research.

The study of imbalance localisation requires many forms of the fault to be tested. Performing this on an actual complex rotating machine (a gas turbine for example) is both costly and impractical, with the possibilities to 'seed' faults being limited. As an initial study, this research therefore relies upon simulation and lab-based rotordynamic rigs. These approaches are commonly used by researchers, as can be seen throughout the literature review. If the work within this study was to progress towards implementation, full scale testing would of course be required. However, in order to achieve the stated aims, the potential provided by such rigs and simulation studies can be considered more than sufficient.

After reviewing the research work by other authors, some approaches to imbalance localisation may be considered not appropriate for this study. The accurate model-based localisation methods such as that by Sinha *et al.*, (2004) have proven to be successful given certain applications (flexible operation in



power generation equipment, for example) – however these approaches are not designed to work in the given criteria for this research. The data-driven approaches typically require excessive amounts of data or multiple sensors, however there is more scope for development in this domain. Despite this the direct approaches by Yang and Hsu, (2010) and Sudhakar and Sekhar, (2011) have very large data requirements across various speed ranges, making these approaches impractical for the purposes of this research. It has therefore been determined that a predominantly data-driven approach supplemented by physics-based simulation has the most potential for development. In an attempt to improve over the large data requirements for some published works, both linear and nonlinear studies are to take place. With this in mind, the following approach has been outlined.

### **3.2.1 Step 1: Investigate a Data-driven Approach**

After a thorough understanding of the problem has been established through the review of literature, an example rotating machine can be used to investigate imbalance localisation. The Spectraquest MFS has been selected for this purpose. The MFS is a multi-purpose rig capable of incorporating a range of rotordynamic faults.

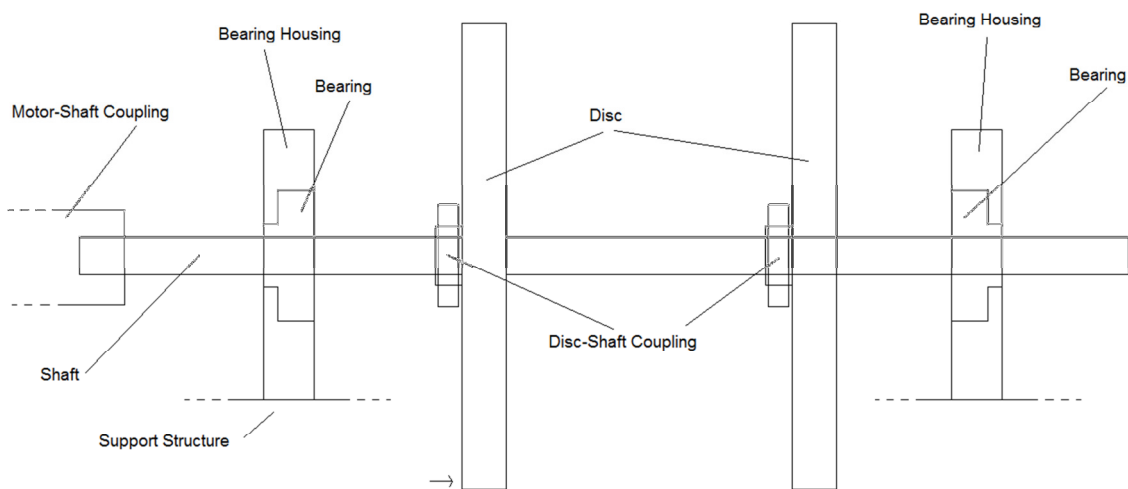
It has already been used by several authors in order to perform cutting-edge research into rotordynamic faults, a pedigree which provides justification for use as a basis in this research. Such machines are commonly used in the first stages of rotordynamic research, as working directly with machinery such as gas turbines is typically costly and difficulties exist in seeding common faults. The MFS can be seen in Figure 3-1 and Figure 3-2. A list of specifications is given in Table 3-1.

Whilst it is intended to identify a novel approach to the problem, it is desirable to use a standardised approach to data collection and interpretation. This allows for any developed technique to have a better opportunity to fit with existing systems for rotating machinery.

A typical process used in a data-driven approach to fault identification and classification in rotating machinery is as follows. This approach is to be used within this research.



**Figure 3-1** Spectraquest MFS



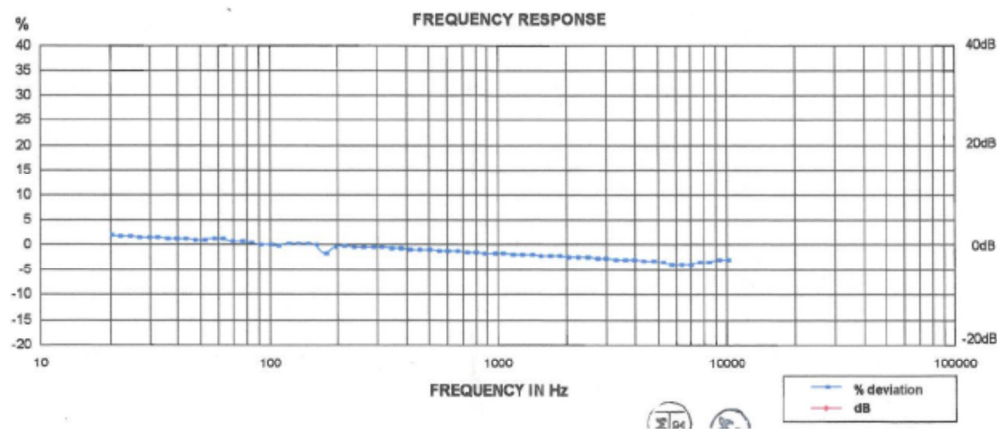
**Figure 3-2** MFS Shaft/Bearing/Disc Diagram (Not to Scale)

Motor	3-Phase, 1HP motor, pre-wired self-aligning mounting system for easy installation/removal
Drive	1HP variable frequency AC drive with multi-featured front panel programmable controller
RPM Range	0-6000 rpm (short duration) variable speed
Current Measurement	Power leads accessible for current measurements
Tachometer	Built-in tachometer with LCD display and one pulse per revolution analogue TTL for DAQ purposes
Voltage	115/230 VAC, Single phase, 60/50 Hz
Shaft	1.9cm diameter, 44.1cm length; Turned, Ground & Polished (TGP) steel
Bearings	Two sealed rolling element in aluminium horizontal split bracket housing for east changes, tapped for transducer mount. Bearing mounts can be mounted in five different positions for variable rotor span.
Rotor Base	45.72cm long, completely movable using jack bolts for easy horizontal misalignment and standard shims for vertical misalignment. Pinned for easy realignment.
Discs	Two 15.24cm radius aluminium with 36 threaded holes at 10 degree intervals for introducing imbalance.
Disc-Shaft Couplings	0.8cm wide aluminium clamp with two adjustment bolts.
Motor-Shaft Coupling	Flexible spiral aluminium clamp with two adjustment bolts.
Foundation	1.27cm die cast aluminium base, base stiffener and eight rubber isolators.
Dimensions	100x63x53 cm

**Table 3-1** MFS Specifications (provided by Spectraquest)

### 3.2.1.1 Sensing

Accelerometers are among the most common sensors used to collect data for rotating machinery. As has been highlighted, in this study, the use of a reduced sensor suite is an important consideration, as is the requirement that the sensors be non-intrusive. For this reason the use of accelerometers is preferred. The calibration curve of a single 98.76 mV/g accelerometer as used in this study can be seen in Figure 3-3.



**Figure 3-3** 98.76 mV/g Accelerometer Calibration Chart

### 3.2.1.2 Signal Conditioning

The next stage involves the conversion of data from analogue to digital, with signal amplification from the sensors also occurring during this step.

### 3.2.1.3 Sampling

Vibration data typically requires a high sampling rate in order to extract relevant features. A trade-off between keeping as much data as possible and the ability to process the stored data is required.

### 3.2.1.4 Filtering

At this point in the analysis, filtering can be implemented. A wide variety of filters can be applied, with functions including noise reduction and restricting

frequency range. This stage enables unwanted data to be removed from the process.

### **3.2.1.5 Short Time Fourier Transform (STFT)**

As discussed in the review of literature, separate domains each have advantages and disadvantages in processing data. Commonly, frequency domain data is of high importance in rotating machinery problems, and therefore conversion from the time to frequency domain is required. This involves application of a STFT.

### **3.2.1.6 Averaging & Normalisation**

Averaging techniques enable a certain amount of variation to be removed, accounting for unwanted peaks and troughs caused by noise in the processed signal. Normalisation enables peaks across the spectrum to be considered relative to each other, rather than in absolute values. Both of these techniques can aid understanding of the phenomena occurring in rotating machinery through the removal of unwanted variation.

### **3.2.1.7 Classification**

Once data has been processed it may undergo classification. A wide range of techniques exist for this, from expert systems to neural network and fuzzy logic approaches.

Using a framework such as this, the investigation of features which can be used for imbalance detection and localisation may be achieved.

## **3.2.2 Step 2: Perform Validation & Test Additional Faults**

After any new system for diagnosing faults in rotating machinery has been designed, it is important to test the system under a wide variety of conditions. Testing as many conditions as possible enables the viability of the system to be assessed, and any correctable issues to be identified. Testing across a variety of machines also enables further validation to be performed, ensuring that the any constructed localisation system is not specific to the MFS. By the completion of this point, the research question “Can a novel system capable of

accurately localising imbalance faults in rotating machinery be developed, relying on a minimal, non-intrusive sensor suite and capable of operating under a wide range of conditions?” can be answered. In addition to validating the system, the research question “Can imbalance localisation be accurately performed when additional faults exist within the system?” may be tackled within this section, with the addition of faults other than imbalance into the test rigs.

### **3.2.3 Step 3: Physics-Based Simulations**

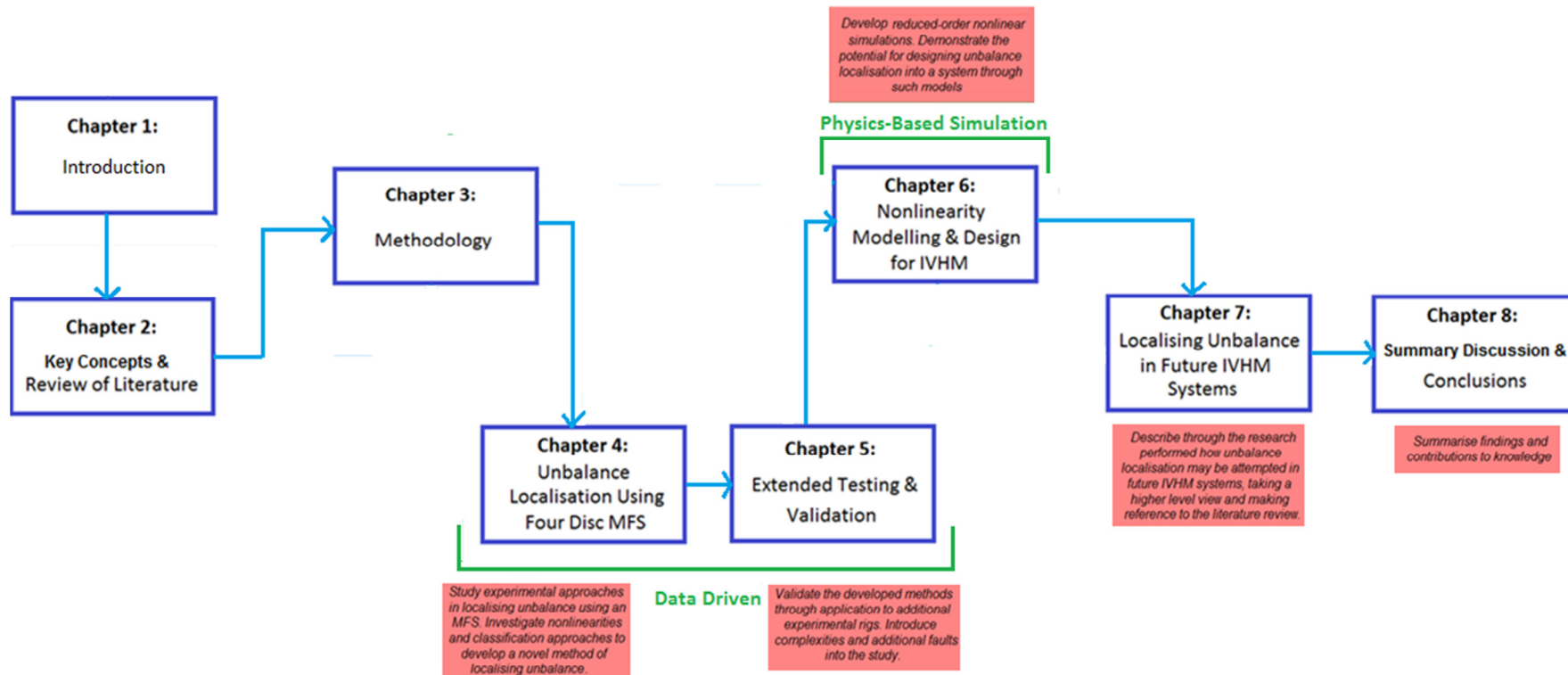
Given the development and validation of a data-driven approach to localise imbalance and, as highlighted in the research questions, it is important to consider how physics-based simulation can aid the data-driven approach in forming a complete picture in localising imbalance. To achieve this, performing physics-based simulations with the new knowledge gained from the data-driven approach can answer the research question “How can a synergy between physics-based simulation and data-driven approaches aid imbalance localisation?”

### **3.2.4 Step 4: Place into Context**

In order to answer the final research question, it is important to put into context the findings from the technical research. Discussing how imbalance localisation may occur in future IVHM systems for rotating machinery provides an important aspect to the project. If the research is to be developed further, and created to be of use to other projects, then production of a generalised methodology and recommendations for implementation in future IVHM systems forms an important final chapter to this thesis. The final research question “Is it possible to create a general methodology for imbalance localisation, taking into account potential application in next generation IVHM systems?” can therefore be answered.

### **3.2.5 Graphical Methodology**

By taking these steps to answer the research questions, the methodology followed throughout this work can be seen graphically in Figure 3-4.



**Figure 3-4** Graphical Methodology Layout

### **3.2.6 Chapter Summary**

In summary, this chapter has outlined the methodology which guides the research undertaken within this thesis. Using the knowledge gained from the review of literature, the method detailed is intended to answer the research questions posed. The following objective has been achieved:

- A methodology has been developed for research into a novel means of localising imbalance in rotating machinery.



## 4 Imbalance Localisation using Four Disc MFS

### 4.1 Chapter Introduction

In this chapter, localising excessive imbalance has been studied from an experimental perspective through the use of a rotordynamic test rig fitted with four discs. Initially, the approach of comparing the 1X (synchronous) vibration amplitude alongside linear harmonics has been used. Following on from this, the effect of imbalance on machine inherent nonlinearities has been studied in order to investigate a viable solution to localise imbalance in rotating machines. In order to automate the procedure, an ANN has been developed and adapted for each case.

Based upon the findings from the review of literature, the proposed theory that inherent nonlinearities may provide features for improved localisation has been studied. As such, the aims of the following section can be viewed as follows:

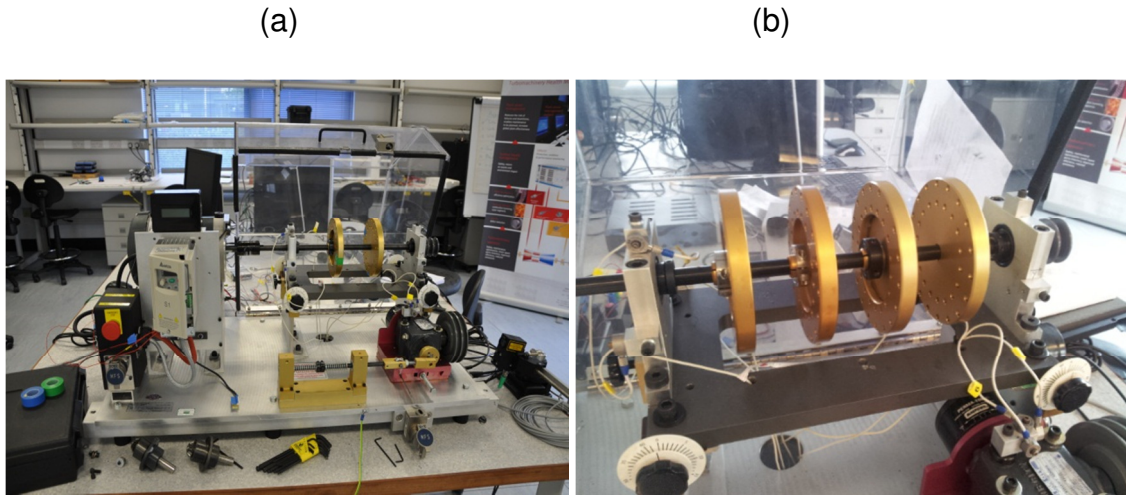
- **Novel Aspect:** Development of a new method for the accurate localisation of imbalance through the use of machine inherent nonlinearities.
- Comparison between ANNs trained using 'linear' and 'nonlinear' features for imbalance localisation.
- Validate the procedure for a wide range of operating conditions

### 4.2 Data Collection & Feature Identification

The initial stages of imbalance localisation require a detailed understanding of the system in question, including an indication of the optimum choice of features for correct fault localisation. This has been achieved through data collection and processing followed by feature identification. These steps are detailed as follows.

#### 4.2.1 Rig Setup

As mentioned, for the purposes of testing and evaluation a Spectraquest MFS has been used, as shown in Figure 4-1 **Error! Reference source not found..**



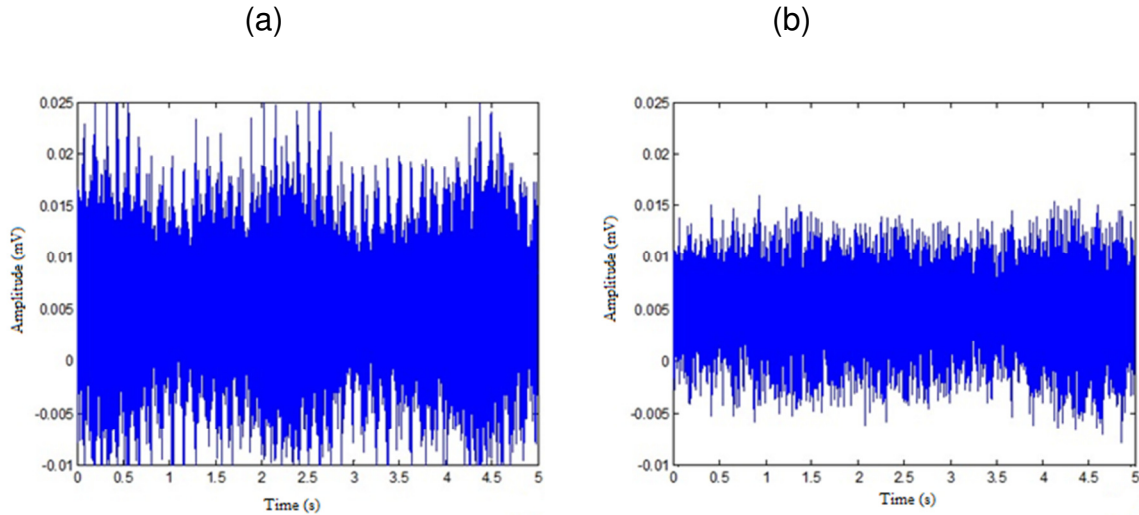
**Figure 4-1** Spectraquest MFS in Standard (a) and Modified (b) Setup

The MFS is a popular lab based system for the study of rotordynamic faults. This includes (but is not limited to) imbalance, misalignment, various bearing faults and various gear faults. The addition of four equally spaced discs (as opposed to the standard two) enable a more complex system to be studied, with localisation taking place between the four positions. This is the maximum number of discs that the MFS can safely accommodate.

For the purposes of data acquisition, six single-axis accelerometers are fitted to the system, with three placed on each bearing housing. Whilst the objective is ultimately to use a single, remotely placed, accelerometer, the use of six initially enabled the vibration response at different positions in different axis. The bulk of the research detailed in this paper has been performed with one single-axis accelerometer placed on the right hand side (from **Error! Reference source not found.**) bearing housing. The effect of combining results from multiple accelerometers is discussed in the final section of results. It can be seen from **Error! Reference source not found.** that the basic vibration signature varies significantly from one bearing housing to the other, as a function of motor and coupling placement.

Data acquisition in this case is performed by a National Instruments analogue to digital interface, with a maximum machine speed of 45Hz, and frequency components between 1Hz and 500Hz considered. The relatively low frequency

range is considered due to considerations for potential sampling, storing and processing constraints in real world applications. This frequency range also enables the first six harmonics to be studied for localisation (1X-6X).



**Figure 4-2** Vibration Signature Recorded from Motor-Side Bearing Housing (a) and Far-Side Bearing Housing (b)

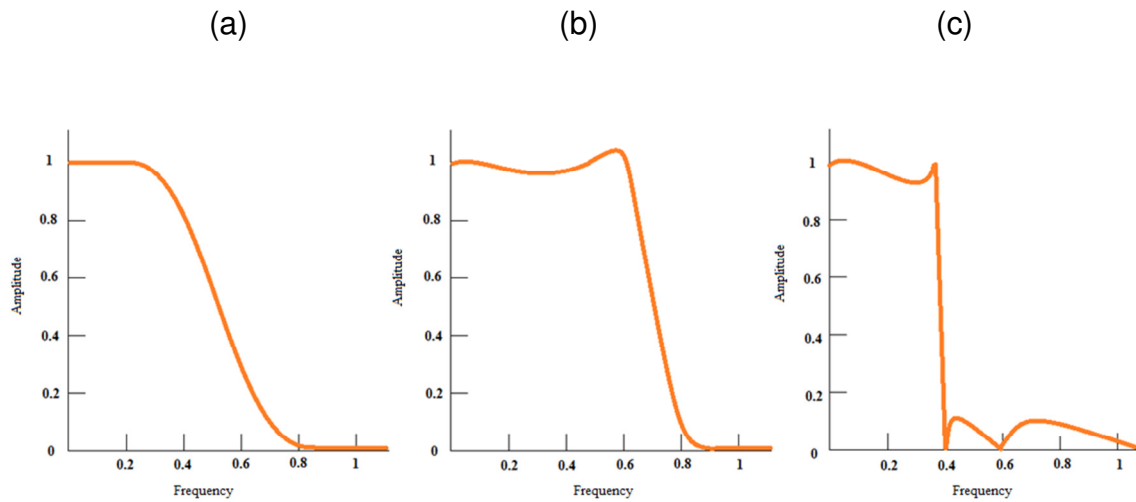
It can be observed from **Error! Reference source not found.** that the vibration spectrum of the MFS is relatively noisy for a rotordynamic rig. The causes for this appear to be numerous, from the mounting of the rig to noise from the electric motor and coupling, surrounding electronic devices, design of the rig in addition to the nonlinearities detailed later in this report. For the purposes of this study, the complex vibration spectrum and large amount of noise can be seen as a benefit. This is due to the fact that industrial machinery and complex systems will typically operate within a much noisier environment than a simple rig, with many more components contributing to the vibration spectrum. Thus, the ability to accurately localise faults under these conditions provides an additional strength for any system designed under these conditions.

#### 4.2.2 Data Collection and Conditioning

The data collection system has been described in more detail in Chapter 2. Throughout this chapter, 20 seconds of steady-state data sampled at 25KHz has been used (found to provide optimum results for the wide range of values

tested). Whilst it may be possible to reduce the sampling rate for a specific application, for testing purposes and feature identification this higher rate has been identified, and subsequently used throughout the work.

In order for the data collected from the system to be analysed, a small number of processing techniques have been applied to condition the data for use. The first stage of this procedure involves a low-pass Butterworth filter, which has been applied due to the smooth roll off in gain detailed in **Error! Reference source not found..**



**Figure 4-3** Frequency Responses with Normalised Units Displaying Gain Roll Off for (a) Butterworth, (b) Chebyshev and (c) Elliptic Filters

This fourth order filter is achieved by cascading two second order low pass filters. The use of such a filter reduces the data required for processing, speeding up the application of ANNs (detailed later in this work). Butterworth low-pass filters are also commonly applied in order to reduce high-frequency random errors created through reconstruction. Following on from this, conversion into the frequency domain has been utilised with the use of a Short Term Fourier Transform (STFT). This in turn enables harmonics to be studied in detail for different signatures between fault positions.

Further to this, small fluctuations in rotational speed (and therefore vibration amplitude) have been removed through the use of normalisation. This is achieved through the division of the STFT value of each frequency with the norm of the STFT vector which contains the values of frequency. The normalised value for a particular frequency is determined using the following relation:

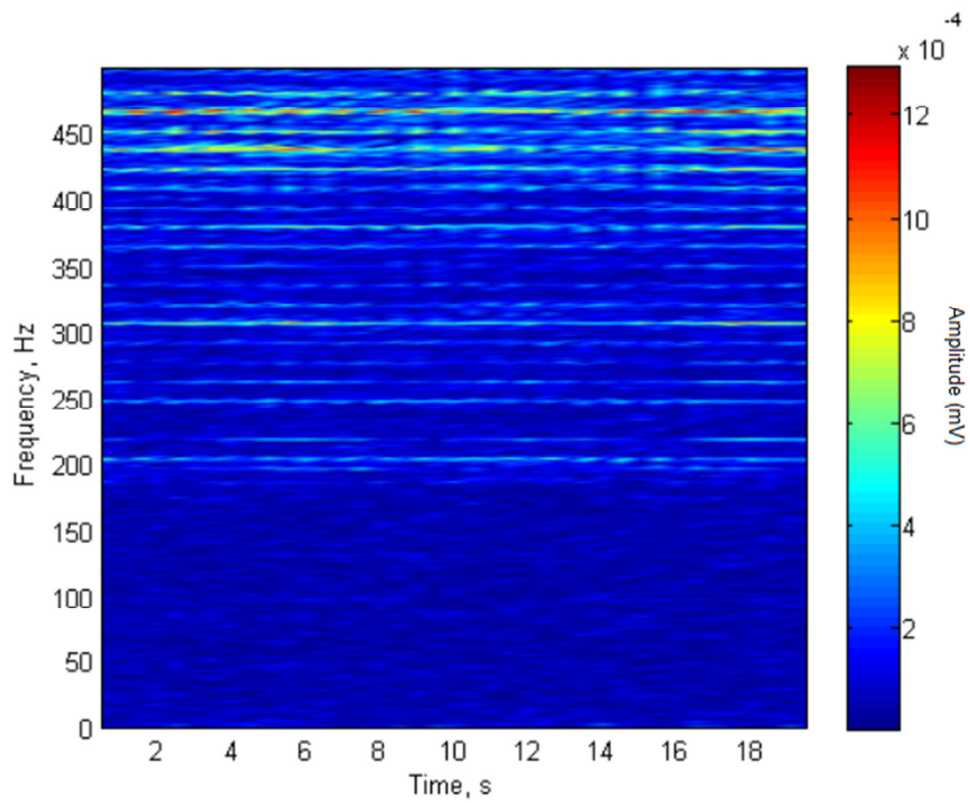
$$\text{Normalised value} = \text{value of amplitude} / \text{norm}(\text{frequency amplitude vector})$$

This preserves the relative strengths of the different frequency components in the frequency spectrum, which is an important aspect to this study. The normalisation procedure is therefore a required step in the processing. In order to detect the position of the imbalance fault it is necessary to consider the changes to the vibration phenomena of the system, and to negate the effects of imbalance size and position relative to the accelerometer.

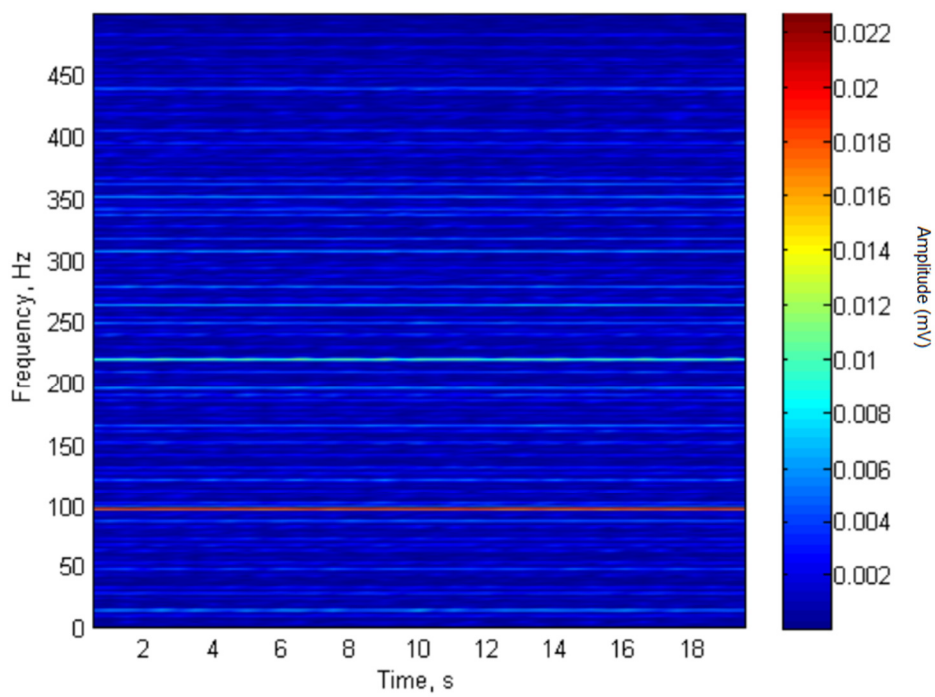
In this way, normalisation can aid the understanding of the vibration phenomena occurring within a system. As one of the primary motives for this technique is operating with a single accelerometer, this provides the driver for such signal processing considered here. Finally, in an attempt to reduce noise in the acquired signal, a time synchronous average has been applied – this removes non-synchronous ‘noise’ (e.g. from mains electricity).

#### 4.2.3 Feature Identification

Prior to the application of the described signal conditioning, the spectrograms displayed overleaf in **Error! Reference source not found.** have been generated (for a speed of 15 Hz).

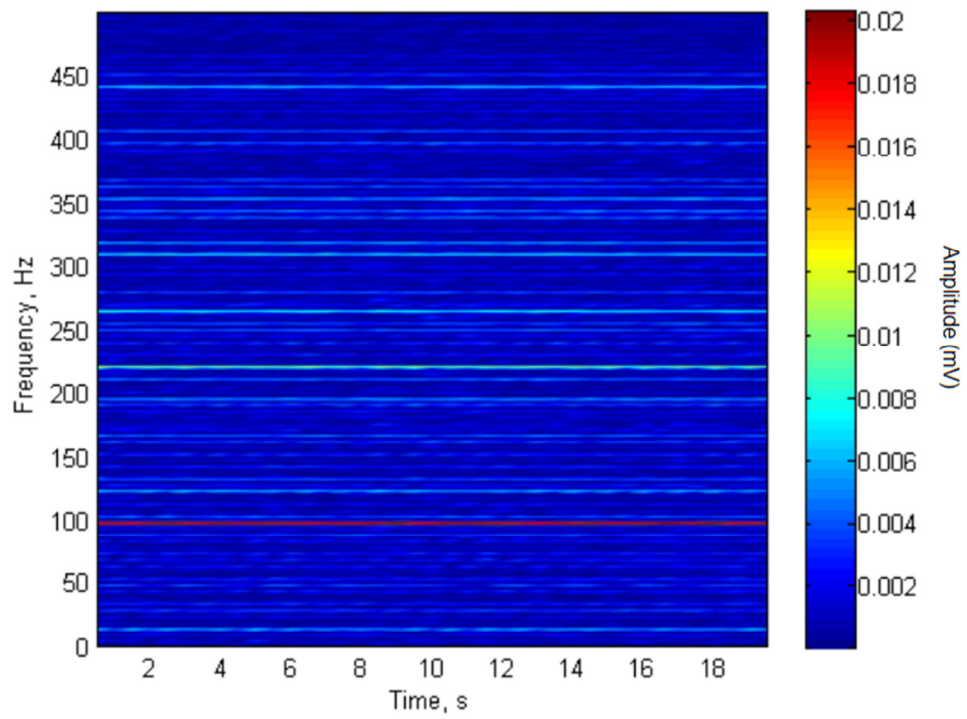


**Figure 4-4 (a):** Balanced

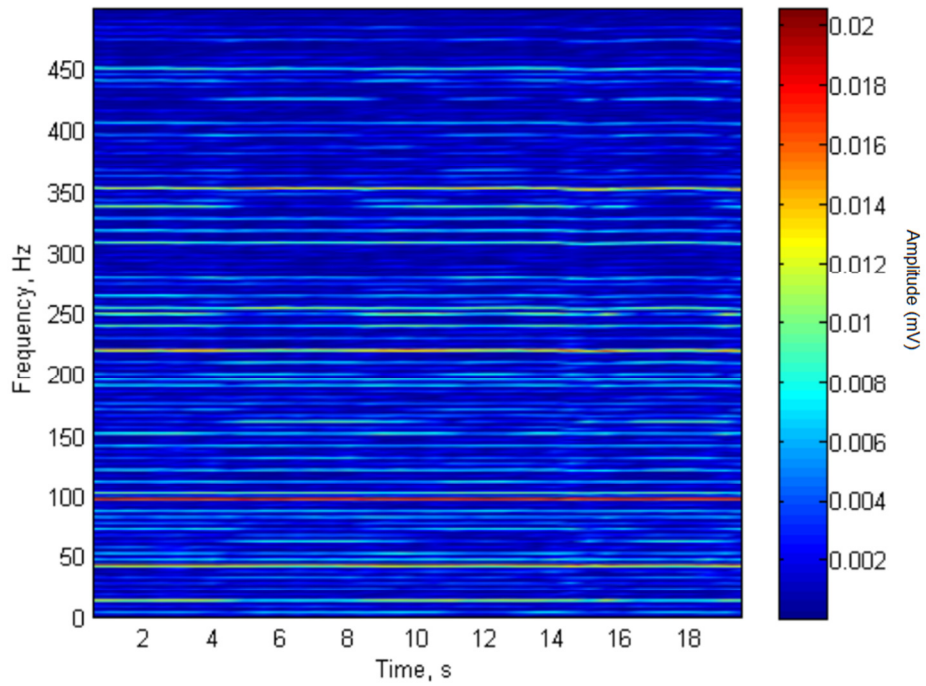


Error! Reference source not found. **(b):** Imbalance on Disc 1

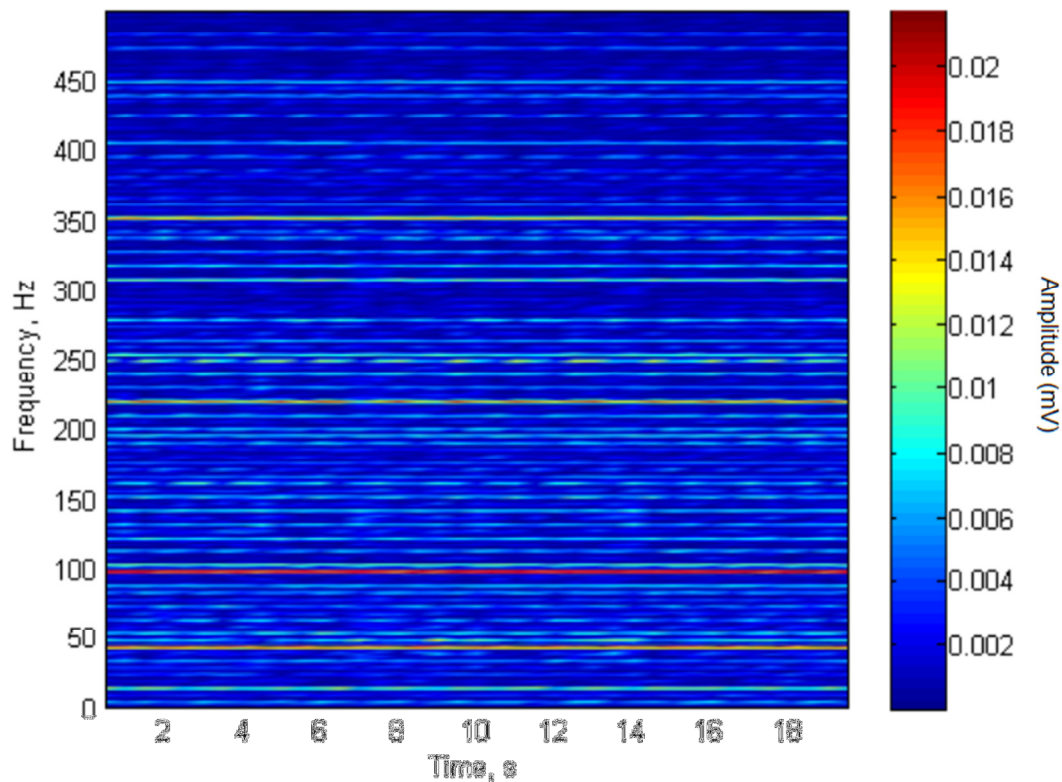




Error! Reference source not found. **(c)**: Imbalance on Disc 2



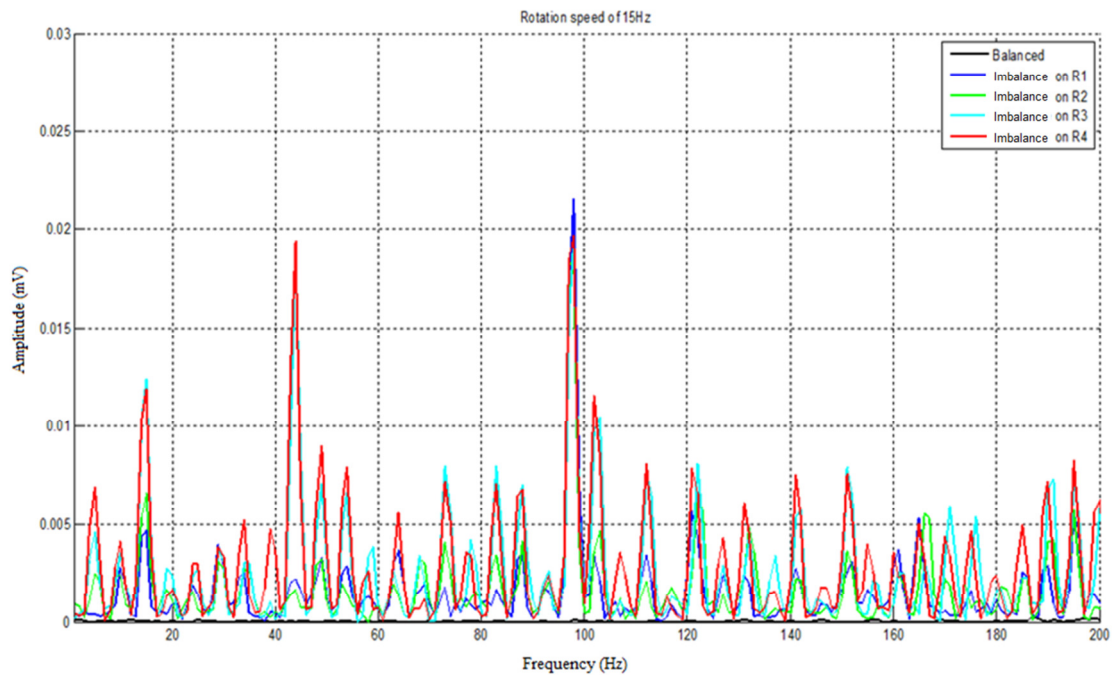
Error! Reference source not found. **(d)**: Imbalance on Disc 3



Error! Reference source not found. **(e)**: Imbalance on Disc 4

For the initial case of localisation, a standard 8.3g static mass imbalance was applied to each disc in turn. Throughout this work, all imbalance masses act at 70mm from the shaft centreline. ‘Disc 1’ refers to the disc mounted at the closest point to the motor, whilst ‘Disc 4’ refers to the farthest. In this initial case, the accelerometer is mounted on the bearing housing farthest from the motor. The study was repeated for a range of speeds (up to 45Hz). In **Error! Reference source not found.** the case for 15Hz can be seen, with distinct variety in the different imbalance cases observed. It can be observed that over the 20 second collection period some periodic fluctuation in vibration amplitude remains. The harmonics which fluctuate in severity can be seen to differ from case to case, indicating the effects of the different imbalance cases on the nonlinearities within the system – a theory tested in the subsequent sections of this paper. Averaging and normalising the vibration amplitude across the 20 seconds of collected data yields **Error! Reference source not found.**, where the relative strengths of the amplitudes of the vibrational data are plotted.





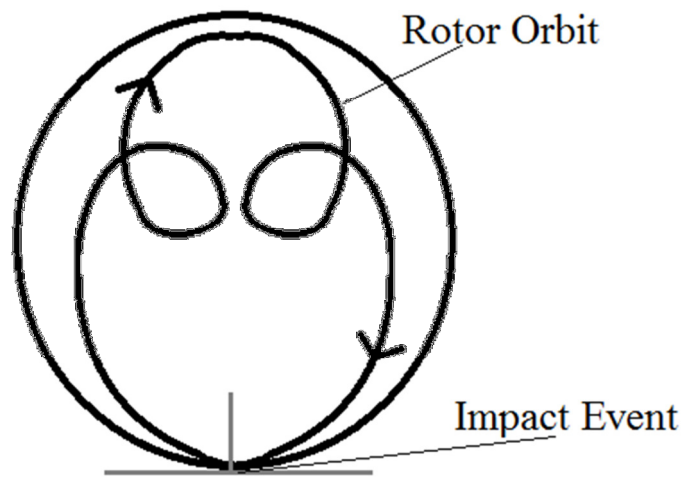
**Figure 4-5** Normalised Frequency Spectrum for Imbalance Localisation Cases.

Although **Error! Reference source not found.** displays the expected result in that, in general, as the imbalance is placed closer to the accelerometer the amplitude of the 1X (and harmonics of this) is larger. The spectrum can also be seen to be relatively complex. Distinct features exist within the studied range, displaying clear differences between the imbalance cases.

From **Error! Reference source not found.** it is possible to identify that harmonic peaks exist not only at integer multiples of the speed of rotation, but also at one third and two thirds of this speed. This proved to be the case for all of the speed ranges studied. The differences between the imbalance positions can be seen to be more pronounced at these points, potentially providing for more accurate localisation features. This can be seen to be the case even after normalisation and filtering. These releases of energy were not predicted by the linear modelling, upon which it can be implied that these characteristics are nonlinear in nature. It can also be seen that the features are clearly excited by the presence of imbalance within the system. The indications are that these one and two-third sub-synchronous harmonics provide a good chance of assisting imbalance localisation for the MFS.

#### 4.2.4 Bearing Clearance Nonlinearity

Upon investigation, the source of the nonlinear feature on the MFS rig was identified as a nonlinear feature arising from slight play of one bearing within the housing. A similar motion can be observed to occur in a chaotic motion under the case of oil whirl, in which such sub-synchronous harmonics are a common feature. In this case however, the whole rolling element bearing can be considered to move within the allowed tolerance of the housing – resulting in similar sub-harmonics, however due to an alternate bearing motion.



**Figure 4-6** Exaggerated Example Orbits of Rotor and Bearing within Housing, Corresponding to an Impact Event Once Every Three Rotations.

This type of nonlinear behaviour is known as a 'gap' or 'clearance' nonlinearity, and has been described in literature by a number of authors. A detailed account has been made by Muszynska and Goldman, (1995), where the authors extensively model such 'chaotic' responses, alongside experimental validation studies with regards to an imbalance force. Wang *et al.*, (2001) detail the use of nonlinearities for fault diagnosis purposes. Ma *et al.*, (2011) detail this effect through a finite element simulation approach. Qiu and Rao, (2005) further discuss these phenomena using a fuzzy approach to an imbalanced rotor.

Whilst the linear approaches to imbalance classification are well established in theory, the effects of certain nonlinearities on imbalance are less well described. A wide variety of nonlinear effects are present in differing degrees in many types of rotating machinery. The degree of the specific nonlinearity identified for the MFS (which may itself be determined a fault if it was deemed to be above allowable tolerances in certain machines) may not be sufficient for fault localisation to take place in many machines. However, it can be demonstrated that even a simple system such as the MFS contains sufficient nonlinear effects to aid localisation; this potential can also be applied to larger, more complex rotating machinery. This subject is described in more detail in Chapter 6.

For the case of the MFS, the design of the system (including easily removable/replaceable bearings) results in this nonlinearity being present to some degree even when the machine is operating under 'normal' setup conditions. The effect appears to be exacerbated by the support structure (a change in damping of the support structure appears to have a noticeable effect upon the nonlinearity). In this thesis, the example results are taken at a rotation speed of 15Hz. It is clear that the speed has a distinct effect upon the vibration signature – however it was found that the one third synchronous harmonics from the nonlinearity remain constant, with different imbalance cases remaining distinguishable within the measured range of 15Hz-45Hz. The ability to locate imbalance accurately implies that the 'gap' nonlinearity is likely to vary slightly between bearings.

#### **4.2.5 Artificial Neural Network**

In order to automate the process of fault localisation, an ANN has been utilised. Other AI (Artificial Intelligence) methods are available for use in such applications, each with distinct advantages and disadvantages. It is not intended for the system used to automate localisation in this project to provide a novel aspect in itself; rather the application is designed to demonstrate that automation is possible and practical for such a system.

With this intention in mind, an ANN was chosen as the AI technique for use in this project on the basis that ANNs have recently become an important

technique for the solution of classification problems. Usage includes detection of bearing faults (Li *et al.*, (1998); Li *et al.*, (2000)) and extensive classification and pattern recognition in the time domain (Samanta and Al-Balushi, (2003)) and frequency domain (Li *et al.*, (2000)). Yu and Han, (2010) used different mode shapes as ANN inputs for the identification of rotor shaft cracks. Barakat *et al.*, (2012) used Self Adaptive Growing Neural Networks (SAGNN) to detect and diagnose a selection of bearing and gear faults. ANNs have also been used to detect mass imbalance in rotating machines McCormick and Nandi, (1997) and for the classification of faults in machines such as turbo-generators Li *et al.*, (2010a). They have also been applied to predict required balance mass correction on imbalance faults Santos *et al.*, (2009).

An ANN performs fault classification through a mathematical model designed to permit machine learning. ANNs are inspired through biological neural networks (such as those in the human brain), and operate through the use of a series of interconnected nodes. Typically, a layer of input neurons feeds to several 'hidden' layers and on to an output layer. The operations performed by each node are 'weighted', allowing for selective flow of data through the network. The weights applied are introduced to the network through a training phase, which can be key to ensuring good performance of such networks. A wide variety of literature exists on ANNs and for a much comprehensive discussion the reader is referred to the extensive work by Yegnanarayana, (2004). The ANN utilised for this study was formulated for use as follows.

Numerous variations of ANN were studied, as a result of this process it was deemed that a 20 second set of data containing 500000 values could provide a suitable set of training data. The ANN was trained using a feed forward back propagation algorithm (using Matlab/Simulink) which adjusts the weights of the connections of the network such that the outputs match the expected values. In the initial study, data was collected for five cases (in the initial case balanced and unbalance in positions 1-4), and repeated for the different speed conditions. From each dataset 39 samples have been used as inputs, classified into one of five outputs (again balanced and unbalance in positions 1-4). The back

propagation algorithm (standard to Matlab/Simulink) feeds each output back through the hidden layers of the network, updating the weights of each connection until sufficient accuracy is achieved. The validation of this involves 156 signals for each type of unbalance and for each speed value. For illustration, four speed values have been detailed (15Hz, 20Hz, 25Hz and 30Hz), however it should be noted that the work has also been conducted for a wide range speeds from 10Hz-45Hz, producing largely similar results to those detailed.

The initial case of ANN testing involved comparison of the different unbalance cases (static unbalance applied to each disc in turn), based upon the straight harmonics in the frequency domain ( $1X - 6X$  in integer values of  $X$ ). This can be considered the 'standard' ANN, as the harmonics can be predicted by linear system models. In order to account for slight variations in speed and noise, the ANN includes a tolerance of  $\pm 0.5\text{Hz}$  for each feature (choosing the peak amplitude from the normalized spectrum). These harmonics are present to some degree across the speed range due to the inherent inaccuracies and tolerances (including the inherent level of unbalance within the machine). The process of normalization detailed therefore enables these harmonics to be considered across the speed range. For this case two single-axis accelerometers on each bearing housing were applied for data collection, and this data does not include any sub-harmonic features.

In **Error! Reference source not found.** the confusion matrix for the training data can be seen, indicating accurate training and validation of the ANN, with 100% of the 156 samples being accurately classified. For training, five sets of training data are fed into the system (one for each imbalance case), each of the 156 samples taken from the training datasets are assessed as to whether they match the expected outcome (for the purposes of validation). In this way the 'Target Class' indicates the expected outcome, whilst the 'Output Class' indicates the actual outcome. This procedure is common to all ANNs described throughout this work.

Confusion Matrix						
Output Class	1	2	3	4	5	
	156 20.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
	0 0.0%	156 20.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
	0 0.0%	0 0.0%	156 20.0%	0 0.0%	0 0.0%	100% 0.0%
	0 0.0%	0 0.0%	0 0.0%	156 20.0%	0 0.0%	100% 0.0%
	0 0.0%	0 0.0%	0 0.0%	0 0.0%	156 20.0%	100% 0.0%
						Target Class
						1 2 3 4 5

**Figure 4-7** Confusion Matrix for Imbalance Localisation Training. Row/Column 1 = Balanced disc, 2 = Disc 1 Imbalance, 3 = Disc 2 Imbalance, 4 = Disc 3 Imbalance and 5 = Disc 4 Imbalance

#### 4.2.6 ‘Standard’ ANN

For illustration, four speed values have been detailed (15Hz, 20Hz, 25Hz and 30Hz), however it should be noted that the work has also been conducted for a wide range speeds from 10Hz-45Hz, producing largely similar results to those detailed.

The initial case of ANN testing involved comparison of the different imbalance positions (static imbalance applied to each disc in turn), based upon the straight harmonics in the frequency domain (1X – 6X in integer values of X). This can be considered the ‘standard’ ANN, as the harmonics can be predicted by linear system models. These harmonics are present to some degree across the speed range due to the inherent inaccuracies and tolerances (including the inherent level of imbalance within the machine). The process of normalisation detailed therefore enables these harmonics to be considered across the speed range. For this case, one single-axis accelerometer on the motor side bearing housing was applied for data collection, this data does not include any sub-harmonic features.

The success of the ANN in predicting the state of the imbalance for the different cases is displayed in Table 4-1. It can be seen that whilst the ANN includes a

degree of success in localising the imbalance, this is not sufficient to consider imbalance localisation successful. Incorrect results occurred due to the ANN confusing imbalance cases with the next closest disc (e.g., confusing imbalance applied to disc 1 as imbalance applied to disc 2).

<b>Rotor Speed</b>	<b>Disc 1</b>	<b>Disc 2</b>	<b>Disc 3</b>	<b>Disc 4</b>
15Hz	75%	75%	70%	75%
20Hz	85%	80%	75%	80%
25Hz	85%	85%	85%	85%
30Hz	85%	80%	85%	80%

**Table 4-1** ANN Success Rates for Imbalance State Prediction Based Upon 1X-6X Harmonics ('standard' ANN).

#### **4.2.7 'Improved' ANN**

In an attempt to improve this, the effects of the detailed nonlinearity (and associated harmonics) were added to the ANN training. In this case the ANN assesses data from 1/3X, 2/3X, 1X, 4/3X, 5/3X and 2X – thus including the nonlinear features alongside the 1X and 2X harmonics.

In Table 4-2 a marked improvement in the ability of the ANN to localise the imbalance fault can be seen, through the application of the nonlinear feature. This includes a 100% success rate when applied to the tested data. Through training the ANN using the two methods mentioned (linear ('standard' ANN) and nonlinear ('improved' ANN)), it can be seen that the addition of the nonlinearities is required for accurate localisation.

<b>Rotor Speed</b>	<b>Disc 1</b>	<b>Disc 2</b>	<b>Disc 3</b>	<b>Disc 4</b>
15Hz	100%	100%	100%	100%
20Hz	100%	100%	100%	100%
25Hz	100%	100%	100%	100%
30Hz	100%	100%	100%	100%

**Table 4-2** ANN Success Rates for Imbalance State Prediction Including Nonlinear Features ('improved' ANN)

#### **4.2.8 Limitation Testing**

Following on from the initial testing and validation, a series of further tests utilising the ANN have been performed with the aim of demonstrating the advantages of utilising the nonlinearities. The results of these are outlined as follows.

##### **4.2.8.1 Sensor Positioning**

The above described tests were performed with one single axis accelerometer placed on a bearing housing. In many types of rotating machinery, this is not possible. In aircraft engines, for example, extreme conditions (including temperature) prevent the accelerometer from being placed in this position. It was therefore decided to test the accuracy of the system when the single axis accelerometer was moved and tested at a number of remote positions (on the rotor supporting structure). During the tests a comparison was made of the ANN including nonlinear features against the 'standard' ANN. It was found that the 'improved' ANN demonstrated a maximum 5% loss in accuracy, whilst the 'standard' ANN displayed a loss in accuracy of up to 15%. The results of this test indicate the advantages of this system of localisation in systems where sensor placement is limited. As long as the transfer path for vibration to the sensor enables the nonlinearities to be picked up, the system can be seen to work accurately.



#### 4.2.8.2 Multiple Plane Imbalance

The initial testing detailed a single plane imbalance. In many cases of imbalance (a build-up of deposits on the discs being one example), imbalance appears in multiple planes. Within the relatively limited abilities of the MFS, the case of multiple plane imbalance was tested, with the following results for two-planes:

	Disc 1	Disc 2	Disc 3	Disc 4
Disc 1	-	100%	100%	100%
Disc 2	100%	-	95%	100%
Disc 3	100%	95%	-	100%
Disc 4	100%	100%	100%	-

**Table 4-3** Two-Plane Imbalance ‘improved’ ANN Results Matrix

The displayed results include the ability to differentiate between single-plane imbalances. It can be seen that accuracy remains high for this case (although it should be noted that additional training for each potential case was required). In addition, three-plane imbalance was investigated, however due to operation limitations with such a high degree of imbalance; this testing was confined to low-speed testing. Despite this, accuracy for this case did not drop below 95%.

In a linear case, different imbalance distributions can appear to cause the same response (dependent on the speed and corresponding mode shape of the machine), thus reducing the ability to localise the imbalance. This issue can be limited through the addition of different accelerometers and the interpolation between the different vibration amplitudes observed. For case of the ANN with included nonlinearities, the complex effects of the nonlinearities at each bearing combined with the speed and operational mode appear to combine in order to negate this effect. This therefore contributes to accurate imbalance localisation

using single speed and accelerometer data regardless of the imbalance distribution.

#### **4.2.8.3 Noise**

Although considered a relatively simple test rig, the data collected from the MFS appears to be relatively noisy. Items such as the electric motor, surrounding electronic equipment (and mains supply) and other lab equipment contribute to this, in addition to the damping effects dependent on the surface on which the MFS is placed. Some of the noise was removed from this study through the use of filtering and consideration for minimising noise from the surrounding environment. The amount of noise can be considered at least partially responsible for the low level of localisation achieved through the 'standard' ANN. A comparison against a relatively noiseless system is detailed later in this thesis.

#### **4.2.8.4 Effect of Imbalance Size**

One of the potential issues of attempting localisation with a single accelerometer is that of differentiating a small imbalance placed close to the accelerometer from a larger one placed further away. In the case of this study, normalisation has been used in order to attempt to remove this effect from the system. Despite this, it is pertinent to assess experimentally the effect of imbalance size on the ANN. In order to do this, a series of test data was collected at three different imbalance weights (in addition to the standard weight). The results for the case of 15Hz can be seen in Table 4-4. As before, all imbalance masses act at 70mm from the shaft centreline.

<b>Rotor Condition</b>	<b>Disc 1</b>	<b>Disc 2</b>	<b>Disc 3</b>	<b>Disc 4</b>
<b>5.0g</b> (Minimum)	45%	45%	50%	55%
<b>7.0g</b> (Light)	90%	100%	100%	100%
<b>8.3g</b> (Standard)	100%	100%	100%	100%
<b>10.1g</b> (Heavy)	100%	100%	100%	100%

**Table 4-4** Imbalance Size Effect on Imbalance Localisation at 15Hz

It can be observed that the ANN is able to successfully localise the position of the imbalance fault to a high degree for all cases except that of the minimum imbalance weight. In this case, the ANN confused the minimum imbalance for the balanced condition. Whilst this indicates that the unique features of the one-third synchronous vibration enable accurate localisation for the case of the MFS regardless of imbalance size, it is limited in the capability to diagnose small rotor imbalances.

#### **4.2.8.5 Effect of Imbalance Type on Localisation**

As part of this study, both imbalance type and imbalance localisation have been considered. As highlighted, imbalance type can have a significant effect on the vibration spectrum of the MFS. Therefore combinations of imbalance type have been studied for the effects on localisation. The results of this study are as follows:

<b>Rotor Condition</b>	<b>Disc 1</b>	<b>Disc 2</b>	<b>Disc 3</b>	<b>Disc 4</b>
<b>Static</b>	100%	100%	100%	100%
<b>Couple</b>	70%	80%	85%	80%
<b>Dynamic</b>	100%	100%	100%	100%

**Table 4-5** Imbalance Type Effect on Imbalance Localisation at 15Hz

The indication from this set of results is that a dynamic imbalance (the most common form of imbalance) is able to be localised as well as the static conditions. However, couple imbalance is again confused with the balanced condition, for the same reasons as previously mentioned. This indicates that one of the main flaws in the proposed system is the ability to detect small cases of imbalance, either through the imbalance being too small to detect, or through incorrect rotor balancing efforts. Despite this, localisation accuracy remains generally high.

#### **4.2.8.6 Machine Rebuild**

It is relatively common for the vibrational features of a machine to be significantly affected after heavy maintenance or rebuild. In order to replicate these phenomena on the MFS, the machine was dismantled, manually checked for any signs of wear, and then rebuilt back to the four disc specification. It was found that, after the rebuild, the ANN was unable to accurately localise imbalance using the existing set of training data. This problem was overcome through the process of capturing a new set of training data. After this, the ANN returned to the high level of accuracy previously detailed. This indicates that, in the case of significant maintenance or machine rebuild, new training data will be required in order to maintain validity of the ANN. The effect is likely caused by the bearing 'gap' nonlinearity being changed slightly as the bearings are removed and replaced in their housings. To re-train an ANN may vary significantly from system to system, and as such this topic is discussed in more detail in the discussion, along with the results from the other studies.

#### **4.2.8.7 Training Data**

During the process of collecting results for this study, the need for accurate training data was realised. Collecting a number of samples, at the same operating conditions yields slightly different data. It was found to be imperative that the data used for training was clear and of good quality if a single data set was to be used. An alternate method to obtain accurate training data involved averaging a number of runs.

Collecting sufficient data in order to accurately train an ANN is a limitation of this artificial intelligence (AI) approach, in particular the collection of data for faulty conditions. However, methods of reducing this limitation exist, dependent on the type of system under study. It must also be noted that training data may be affected by wear, changing throughout the normal operating cycle of a machine. This is discussed in further detail later in Chapter 7.

### **4.3 Chapter Discussion**

Throughout this chapter, the development of a novel method for the accurate localisation of imbalance through the use of machine inherent nonlinearities has been detailed. Whilst further research is required in order to validate and adapt the methodology (detailed in the following chapters), the implications are the through the use of nonlinear features, accurate imbalance localisation may be accurately performed.

In the case of the MFS, a nonlinearity present through the amount of play of the bearings in their housing appears to invoke a unique response when different imbalances are applied. This, in turn, enables accurate localisation of the imbalance fault even when a single accelerometer is used. It is believed that this high localisation accuracy is possible as the gap nonlinearity varies slightly between bearings.

It can be seen from the work detailed that the localisation has been performed with success for the case of the MFS fitted with four rotors. The process of filtering and normalisation has enabled accurate localisation to be performed using the ANN regardless of imbalance size or type (within the given constraints

of the MFS). This provides an encouraging example that localising faults in rotating machinery is achievable for the purposes of improved diagnosis and maintenance. However, as this chapter describes an initial study into the problem, it is necessary to discuss some of the remaining issues with the detailed system.

One of the main limitations of the system in its current state is that the imbalance has been detailed as the only fault occurring in the system. To this end, diagnosing imbalance can be viewed as ‘straightforward’ in the sense that it cannot be confused with other faults. As previously described, imbalance can be a function of many root causes – misalignment providing one common example. A natural evolution of the described methodology involves the inclusion of other faults into the ANN, in order to provide not only imbalance localisation but root cause analysis.

It can also be noted that the training data obtained here, although containing slight variations in speed, can generally be considered to be collected during steady state conditions. Whilst collecting steady state data in some industrial applications (e.g. power generation) can be achieved with relative ease, in other cases this is not so. Further development of the imbalance localisation system described here could involve the application of ‘run-up, run down’ data into the ANN training and validation stage. This would enable the system to be adapted further for use in a range of systems.

Several other factors need to be taken into account when furthering the development of the localisation system. These include the requirement for collecting training data for the ANN. This limitation is discussed by a number of authors including Kumar *et al.*, (2012) and Srinivas *et al.*, (2010). One potential approach to circumnavigate this limitation involves the collection of faulty operating data for one system, whereby trending data is then applied to a similar system. This is an avenue of research in the field of gas turbines in particular, wherein the potential exists to seed faults and collect training data for specific (often previous generation) turbines fitted to test rigs. The study of

localisation and nonlinear features can then be inferred for later generations of turbine.

The latest developments into finite element modelling of whole engine models (Rao, (2011)) alongside nonlinear simulation techniques (Sinou, (2009); Gupta *et al.*, (2011)) are beginning to provide scope for developments in this area. One further consideration with the detailed system of localisation includes a slightly reduced ability accurately diagnose imbalance under certain conditions, such as small imbalance weights or couple imbalance. In some systems, even a small imbalance outside of the given tolerance can be seen to be unacceptable (no machine is perfectly balanced). One possible solution to this problem, requiring further study, is the combination of a separate system to diagnose imbalance in the first instance (as discussed, many of these have been researched). Upon detection of the imbalance, the localisation ANN could be run. This would have the effect of removing the balanced case from the equation, thus forcing the ANN to determine a disc for the imbalance.

Despite the detailed topics requiring further research, it is anticipated localisation approaches such as this have the potential for practical applications in the improvement of maintenance in complex rotating machines. The inclusion of nonlinear features appears to reduce the requirement for more advanced, expensive and potentially impractical sensor suites in order to achieve the same level of localisation. In addition, the nonlinear approach to imbalance localisation has several advantages over the linear approach.

The complex interactions caused by the imbalance fault on the nonlinearities of the machine results in specific vibration spectrums dependent on the imbalance case. In the linear domain, these interactions are predictable and repeatable. A simple example of this is indicated by a small imbalance placed close to the accelerometer, which can display an almost identical linear response to an equivalent larger mass placed further from the sensor. Depending on the machine, the interactions between the structure, nonlinear bearing effects, fault position and other effects enable each imbalance case to be considered with a specific response, thus enabling the improved accuracy over the linear

approaches. This new approach to imbalance localisation represents a contribution to scientific knowledge.

#### 4.4 Chapter Conclusions

In this chapter, the following aims have been achieved (as published, see Appendix F):

- **Novel Aspect:** A new method for the accurate localisation of imbalance has been proposed and tested extensively through study of a four disc MFS.
- Comparison between ANNs trained using 'linear' and 'nonlinear' features for imbalance localisation resulted in a clear advantage for the 'improved' ANN.
- Validation has been performed through extensive analysis on the MFS.



## 5 Extended Testing & Validation

### 5.1 Chapter Introduction

The described system of imbalance localisation has therefore been applied to the MFS with a high level of success. In order to further develop and validate the described system, two additional aspects have been introduced through the course of this chapter. The first is the ability to localise imbalance even in the presence of other faults. As described in the review of literature, imbalance can occur as a 'pure' fault, or as a function of another underlying fault. It is therefore important to consider that the proposed system of imbalance localisation is capable of accurate results even when other faults are involved. Any of the eight common rotordynamic faults may be tested for this purpose, however misalignment and rub faults have been chosen in this case. Misalignment due to the close links with imbalance, and as it may be an underlying cause, and rub which may be a secondary fault caused by imbalance. Misalignment, Imbalance and Rub may all be present at the same time (and separately). In addition, the MFS has a wide scope for implementing these additional faults.

Re-balancing a machine when a misalignment (for example) is the underlying cause can result in the core fault going undetected, and potentially causing further damage to a machine. It is important to note that the focus of this work remains imbalance, as the detailed study of each individual rotordynamic fault is complex and beyond the scope of this work. As such, the aim is to continue to study imbalance, however with other 'root causes' involved.

Secondly, it can be seen from the previous chapter that the developed system works well for the case of the MFS, with a machine specific inherent nonlinearity. In order to assess the potential adaption of the localisation system to other machinery two further cases have been studied. This takes the form of two alternate rotordynamic rigs, with significantly different features, layout and operating conditions from the MFS. This enables the adaption and applicability of the system to be studied through these alternate case studies.

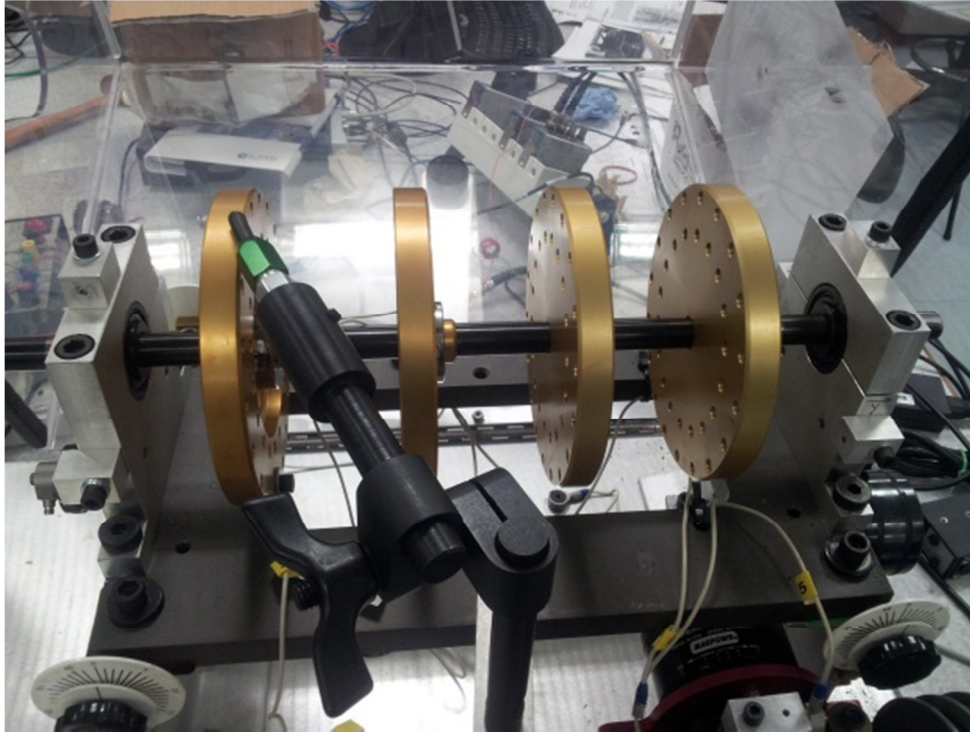
- **Novel Aspect:** Adaption of the imbalance localisation system for use in two alternate rotordynamic rigs.
- **Novel Aspect:** Development of the imbalance localisation system to work with underlying faults, including rub & misalignment.

## 5.2 Case 1: MFS

In the first of three cases within this section, extended testing has been performed upon the MFS. Adding to the previous work, two additional faults have been combined into the study. These chosen faults are rub & misalignment – both of which can be linked to imbalance faults in rotating machinery. It is also possible to easily combine and control these faults on the MFS.

Two approaches to this have been performed in order to tackle this complication. The first approach is to integrate all of the combinations of imbalance/misalignment/rub alongside fault positions into a single ANN. The second approach involves training two separate ANNs, the first of which deals with fault diagnosis (no fault, imbalance, misalignment, rub and combinations of these); the second localises imbalance (when the first has detected its presence).

It is the intention of this section not to quantify and localise the misalignment and rub faults, instead it is intended to localise imbalance even in the presence of these other faults. Initially, the two faults were introduced with the original ANN, in order to quantify the effects of this upon the original training. The misalignment applied in this case is a 1mm parallel shaft displacement at the motor side bearing, allowed for due to the use of a flexible motor/shaft coupling. The rub is performed through a hard rubber contact applied as displayed in **Error! Reference source not found..**



**Figure 5-1** Example Rub Fault Applied to MFS

The results of this approach can be seen in Table 5-1, where a slight loss in accuracy is identified when the rub and misalignment are applied. Whilst the performance of the ANN is still strong, industrial application would require >99% accuracy and therefore improvement in these techniques is still desired. Table 5-1 therefore indicates the success rates of imbalance localisation in the case of other faults.

<b>Fault Applied</b>	<b>Disc 1</b>	<b>Disc 2</b>	<b>Disc 3</b>	<b>Disc 4</b>
<b>Pure Imbalance</b>	100%	100%	100%	100%
<b>Misalignment + Imbalance</b>	90%	95%	90%	90%
<b>Rub + Imbalance</b>	95%	95%	95%	95%

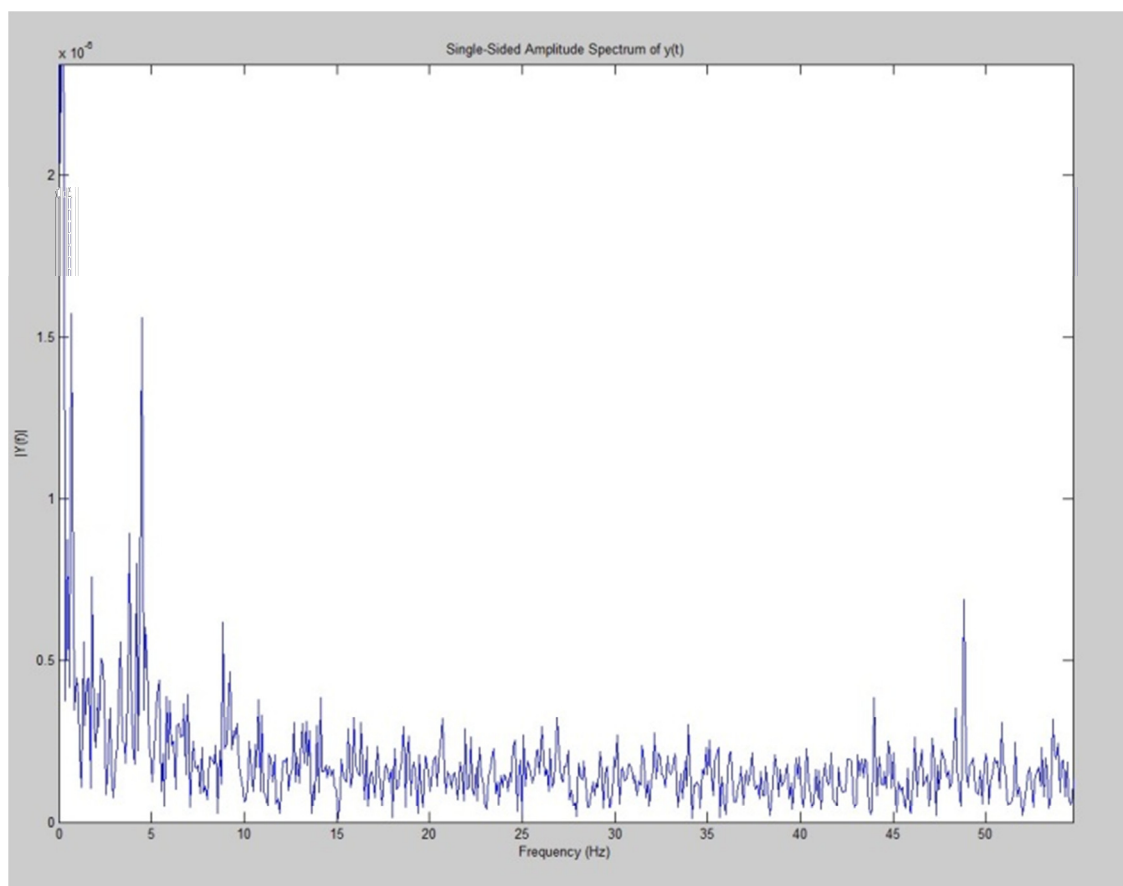
**Table 5-1** Effect of Additional Faults on Original ANN

With the aim of improving the ANN to meet this stated level of accuracy additional training was performed. It was found that, as expected, if the ANN contained training data for every fault condition and imbalance location then the level of accuracy returned to 100%. However, this amount of training data is, in practice, highly difficult to obtain in many types of rotating machinery – and therefore an improved method of training was required. Upon additional testing, it could be ascertained that in order for accuracy to return to 100%, the ANN could be trained using a combination of rub and imbalance data. This then enables imbalance to be localised regardless of the underlying faults.

However, once again, this is of limited value. Balancing a machine when an underlying fault is causing the effect does not solve the root cause and can lead to further issues. Thus an alternative method has been devised. In this case, the same dataset passes through two ANNs. The first of these identifies if imbalance is present, along with rub or misalignment – whilst the second localises the imbalance (if present). The inputs to the ANN in this case remain the same as discussed in Chapter 4. The potential outputs for the first ANN include: No Imbalance Found, Imbalance Only, Imbalance & Misalignment and Imbalance & Rub. The outputs to the second ANN are: Imbalance in Position 1, Position 2, Position 3 and Position 4 (as per the work in Chapter 4).

As the three specified faults display distinct combinations of spectrum, along with clear effects on the nonlinearity, the accuracy of this ‘initial’ ANN is high (100% across all tested cases). In **Error! Reference source not found.**, an example FFT can be seen for the combined case of rub/misalignment/imbalance. This spectrum is clearly different to that in **Error! Reference source not found.**, for pure imbalance. In this case these combinations of faults have such a severe and highly undesirable effect upon the system that the nonlinearities in the bearing become highly undesirable. However it stands to highlight the different effects that can be observed on the system.

After initial fault detection, imbalance localisation can be performed. In the case of the MFS, it was found that the effects of rub and misalignment could be accounted for by expanding to include a 1Hz band (as opposed to 0.5) into the ANN in order to correct for effects of the faults on the machine speed and resultant nonlinearities. This allows for the high accuracy of imbalance localisation to be maintained (again, 100% for all tested cases). This 'dual ANN' approach also requires less training data to be required, due to the reduced number of fault combinations. In the case of the MFS, the 'pre-screening' ANN determines the presence of additional faults through a comparison of the 2/3X nonlinearity and the 1X peak. This functions with 100% tested accuracy due to the fact that the relative amplitudes of these two points differ significantly when an imbalance also has a rub or misalignment present.



**Figure 5-2** Combined Rub/Misalignment/Imbalance Faults for 14Hz Operation

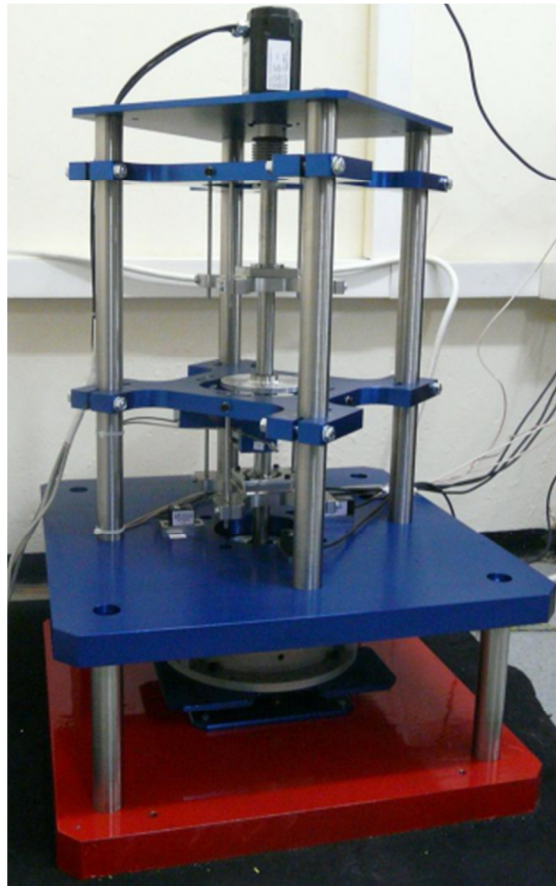
### 5.3 Case 2: Technion Institute Rig

It has been demonstrated that the ANN has successfully been trained to localise imbalance across the four disc system of the MFS, with localisation significantly improved through the application of sub-synchronous nonlinear phenomena. In order to move this approach from a system specific application towards a general method for imbalance localisation, the detailed ANN has been applied to a second rotordynamic rig. In this case, the rig varies significantly from the MFS, as can be seen in **Error! Reference source not found.**

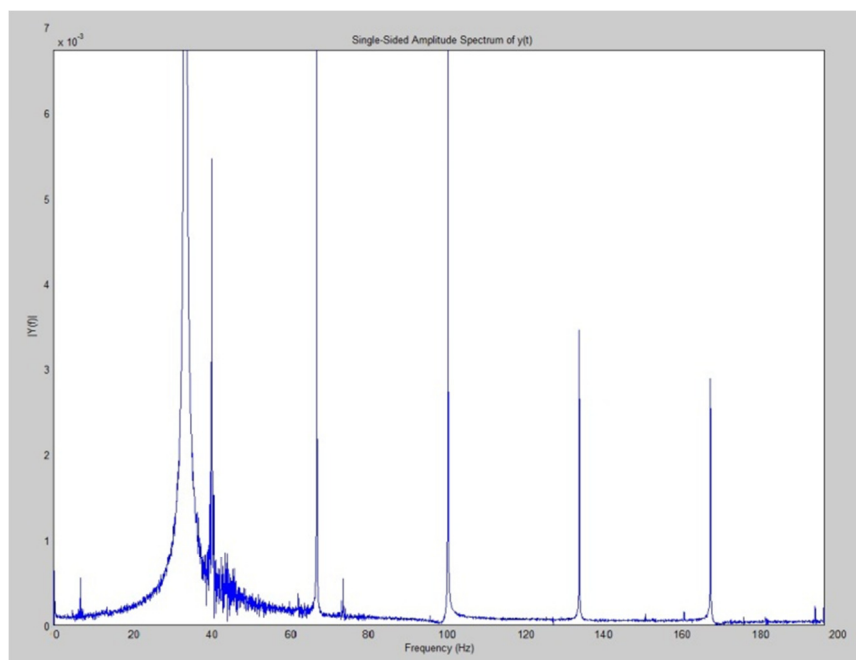
#### 5.3.1 Initial Testing

This setup includes two discs on a single rotor system, supported by two self-aligning ball bearings. In this case, imbalance is to be localised between the two discs. The procedure for setting up the ANN follows the same pattern, with a constant speed frequency spectrum first inspected for features. This can be seen detailed in **Error! Reference source not found.**, where the dominant peak of the 1X vibration plus the harmonics can be seen, in addition to some energy in the spectrum outside of these points. For the purposes of comparison, an ANN has been trained based upon the first six harmonics of the 1X vibration (1X – 6X), each for three conditions (balanced, imbalance position 1 and imbalance position 2). This ANN is again referred to as ‘linear’.

It can be seen from **Error! Reference source not found.** that the operation of this rig is much smoother to that of the MFS, in part due to the smaller number of rotating parts within the system and a finer degree of balancing having been applied. In the case of the balancing rig, data collection is provided by two proximity probes – located on the support structure of the machine and remote from the bearing points. Data collection for the ANN follows the same format as that for the MFS. As this system consists of only two discs and is a low-noise system, the level of localisation achieved through this approach was high. Despite this, 100% success across the tested data was not achieved, as can be seen in Table 5-2 with some error still occurring.



**Figure 5-3** Technion Institute Balancing Rig



**Figure 5-4** Single Sided Amplitude Spectrum at 33.3Hz Speed

	Balanced	Imbalance Disc 1	Imbalance Disc 2
<b>8.3Hz</b>	95%	90%	90%
<b>16.7Hz</b>	100%	90%	95%
<b>25Hz</b>	95%	90%	95%
<b>33.3Hz</b>	100%	95%	95%

**Table 5-2** 'standard' ANN Localisation Success Rate

Following on from this, a return to the frequency spectrum for the purposes of identifying nonlinearities can be performed. In this case, and as displayed in **Error! Reference source not found.**, at 1/6 rotation speed (~5.6Hz) a small peak of energy can be observed, from an unknown nonlinearity within the system. This small energy leakage appears to be affected by the imbalance state within the system (most likely occurring from one or more bearings). Whilst other sources of energy leakage appear to be present in **Error! Reference source not found.**, further analysis indicates that these features either vary with rotor speed or do not vary with imbalance position. Re-training the ANN in order to take into account the effect of this small nonlinearity yields the success rates detailed in Table 5-3.

	Balanced	Imbalance Disc 1	Imbalance Disc 2
<b>8.3Hz</b>	95%	90%	90%
<b>16.7Hz</b>	100%	100%	100%
<b>25Hz</b>	100%	100%	100%
<b>33.3Hz</b>	100%	100%	100%

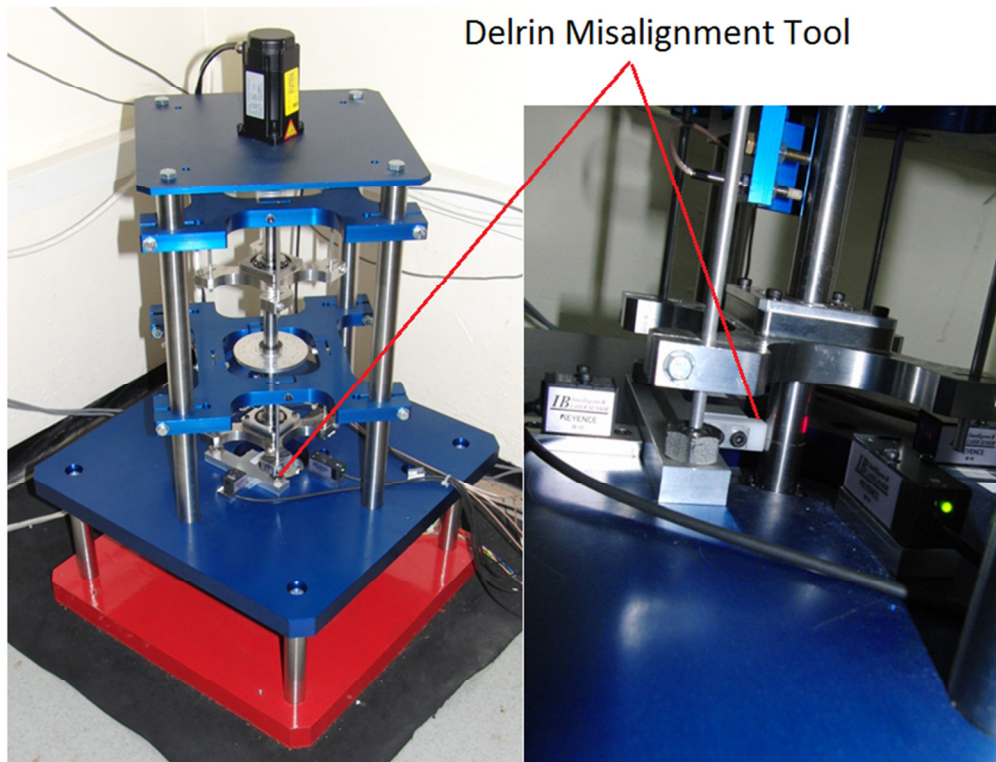


**Table 5-3** ‘improved’ ANN Localisation Success Rate

It can be seen that the ability of the ANN to localise the faults is once again improved by the inclusion of the nonlinearity into the system. In the case of 8.3Hz, this particular nonlinearity is masked by the dominant (1X) frequency due to the slow speed of the rotor, contributing to the reduced accuracy in localisation.

### 5.3.2 Misalignment and Run-up, Run-Down Testing

The initial testing indicates that the ANN can easily be adapted for use in the Technion balancing rig. The initial case demonstrates only the improvement in pure imbalance localisation for the two given positions. As with the MFS, an additional fault needs to be seeded into the system in order to test the ability of the ANN to localise imbalance even in the presence of underlying causes. In this case, a misalignment is induced into the system through the application of a specially manufactured part (which can be seen in **Error! Reference source not found.**).

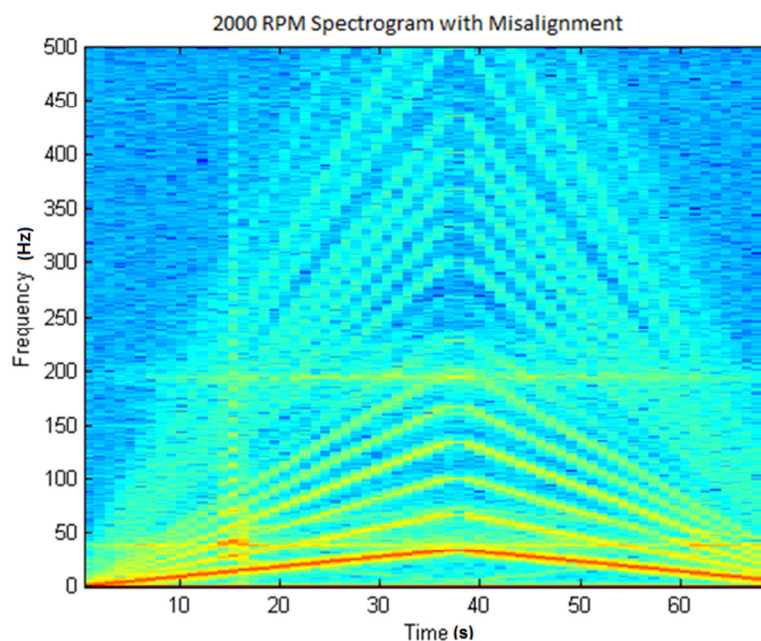


**Figure 5-5** Technion Rig with Misalignment Tool

The part is manufactured of a high stiffness, low friction thermoplastic (Polyoxymethylene) referred to as 'Delrin'. This part forces a small misalignment of the shaft (values up to 1mm), although in a different mechanism to that used for the MFS. This misalignment can also be said to incorporate a 'rub' fault due to the contact between the Delrin part and the shaft. Whilst this setup enables the additional fault to be studied, in order to preserve the Delrin misalignment part, constant high speed test running is no longer possible with this setup. This added complication is indicative of potential issues within more complex rotating machinery – if a fault is detected, it is undesirable to run the machine at high speed with a known fault.

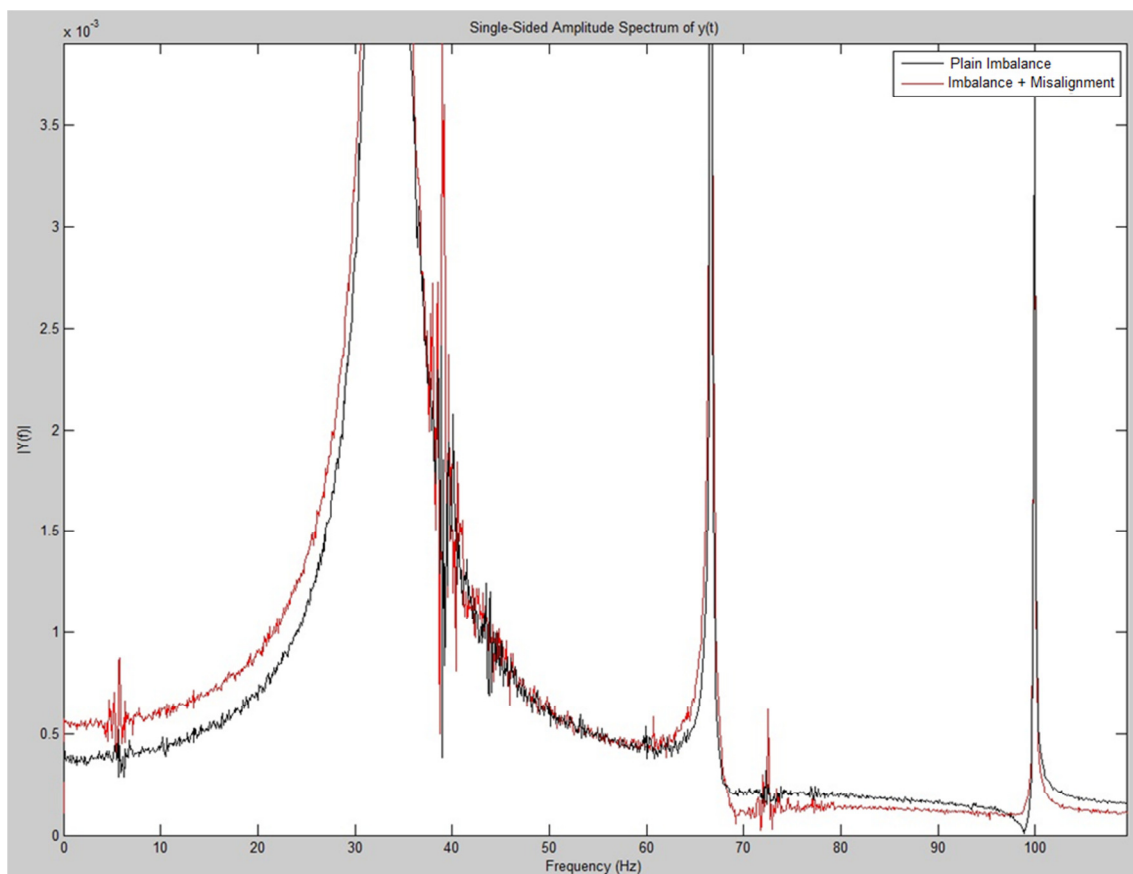
Thus, in addition to adapting to the misalignment part, in this case the ANN required adaption to a 'run up, run down' scenario. This type of run is common in rotating machinery as part of 'pass-off' testing, which is a basic systems check before a part is approved for full operation after construction or heavy maintenance. As such, adapting the ANN for this scenario is beneficial in the development of the localisation system.

A spectrogram from the operation of the rig during such a run, with the misalignment applied, can be seen in **Error! Reference source not found..**



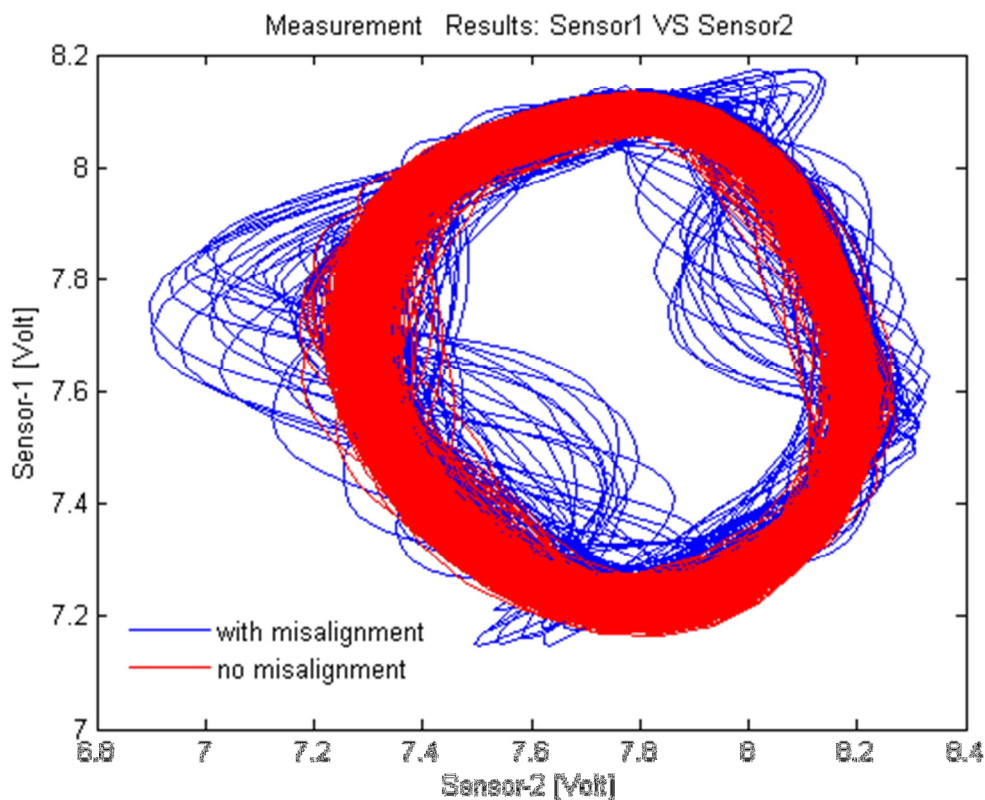
**Figure 5-6** Run-up, Run-down Spectrogram with Misalignment

The spectrogram demonstrates the linear acceleration of the machine up to 2000RPM (33.3Hz), followed by the linear deceleration back to static conditions. The 1X and harmonics of this can be seen clearly within the spectrogram, however nonlinearities outside of this are not clearly visible. In **Error! Reference source not found.** a comparison of the frequency content of the spectrum at the point of maximum speed (33.3Hz) can be seen, with an imbalance applied to the upper disc compared against the same imbalance with a fitted misalignment. In this comparison, the 1/6X harmonic can be seen to increase in amplitude when the misalignment is applied. It is also worth noting that the energy in the spectrum around 72Hz is unique to the misalignment case.



**Figure 5-7** Frequency Domain Imbalance & Misalignment Comparison

This additional nonlinear effect enables the misalignment to be clearly differentiated from the plain imbalance case, across the speed range. As the standard instrumentation on this rig consists of two proximity sensors positioned on the same plane, the relative motion of the shaft can be plotted for the two cases, as can be seen in **Error! Reference source not found.** In this plot an occasional deviation in the shaft displacement can be observed for both cases – however with a much greater magnitude for the misalignment case, indicative of the increased energy in the frequency spectrum in the sub-synchronous region used for imbalance localisation.



**Figure 5-8** Orbit Plot Comparison

In the first instance, the ANN required adaption for changing speeds. In the case of the run-up, run-down scenario, the linear acceleration in a given time to reach a known speed and back down to stationary enables accurate 'order tracking' to be implemented. Instead of the same speed value being applied to all data points (for the input to the ANN), a function of linear acceleration

enables the speed to be calculated at each point based upon the time stamp. The rotational speed at each data point is then known and the amplitudes of the orders can be tracked and averaged as before, for implementation into the ANN. In this case the sampling rate remains at 25Khz, however the length of the sample has been varied to match the machine operation.

Through the application of this to the ANN, the following results can be obtained (Table 5-4).

<b>Maximum Speed</b>	<b>Balanced</b>	<b>Imbalance Disc 1</b>	<b>Imbalance Disc 2</b>
<b>16.7Hz</b>	100%	100%	100%
<b>25Hz</b>	100%	100%	100%
<b>33.3Hz</b>	100%	100%	100%
<b>35.8Hz</b>	100%	100%	100%

**Table 5-4** ANN Imbalance Localisation Success Rates for Run-up, Run-down (with Misalignment).

It can be seen that a high success rate has been achieved through the test speeds when the order tracking is implemented. The range of different responses interpreted throughout the speed range provides added differentiation for the purposes of localisation, hence the high success rate.

It can be found from **Error! Reference source not found.** that the features used for localisation are amplified when the misalignment is applied. Following from the example in Case 1 for the MFS, an initial 'diagnosis' ANN can be created which determines the presence of imbalance or misalignment. For this, the energy released close to the second harmonic (as described and visible in

**Error! Reference source not found.**), provides a good ‘screen’ in order to identify the underlying presence of misalignment.

### 5.3.3 Technion Rig Testing Conclusions

The testing undertaken with the Technion Institute balancing rig demonstrates the adaptability of the localisation technique. This occurs despite the lack of any obvious bearing nonlinearity at 1/3 rotation speed, as utilised by the MFS system, in addition to a rig with a very different setup. It has been found that this rig also possesses nonlinear effects in the sub-synchronous regime, with which improved imbalance localisation can be achieved when incorporated into the ANN. With the addition of misalignment faults into the machine, the energy released by this nonlinearity increases, and it can be seen that a corresponding deviation in the periodic motion of the shaft can be observed. Despite the addition of the misalignment fault, high imbalance localisation accuracy is still possible across the two positions. Achieving this has also required the adaption of the ANN to track the necessary nonlinearities across a run-up, run-down scenario.

## 5.4 Case 3: Cranfield School of Engineering Balancing Rig

Up to this point in the research, the system for imbalance localisation using machine specific nonlinearities has been developed for the MFS, tested for different scenarios, advanced to work with additional ‘underlying’ faults and adapted for use on the Technion rotordynamic rig. The final stage of experimental studies and validation for this approach involved the application to one further rotordynamic testing rig. This rig displays a setup distinct from both the MFS and Technion machines, which can be seen in **Error! Reference source not found.**. In this case, two discs are supported by three oil lubricated bush type bearings. Each disc represents a large mass with a small diameter, distinct from both the MFS and Technion rig. The machine also possesses an obvious and well established first critical speed, enabling efficient testing of the imbalance localisation in both rigid and flexible shaft scenarios.

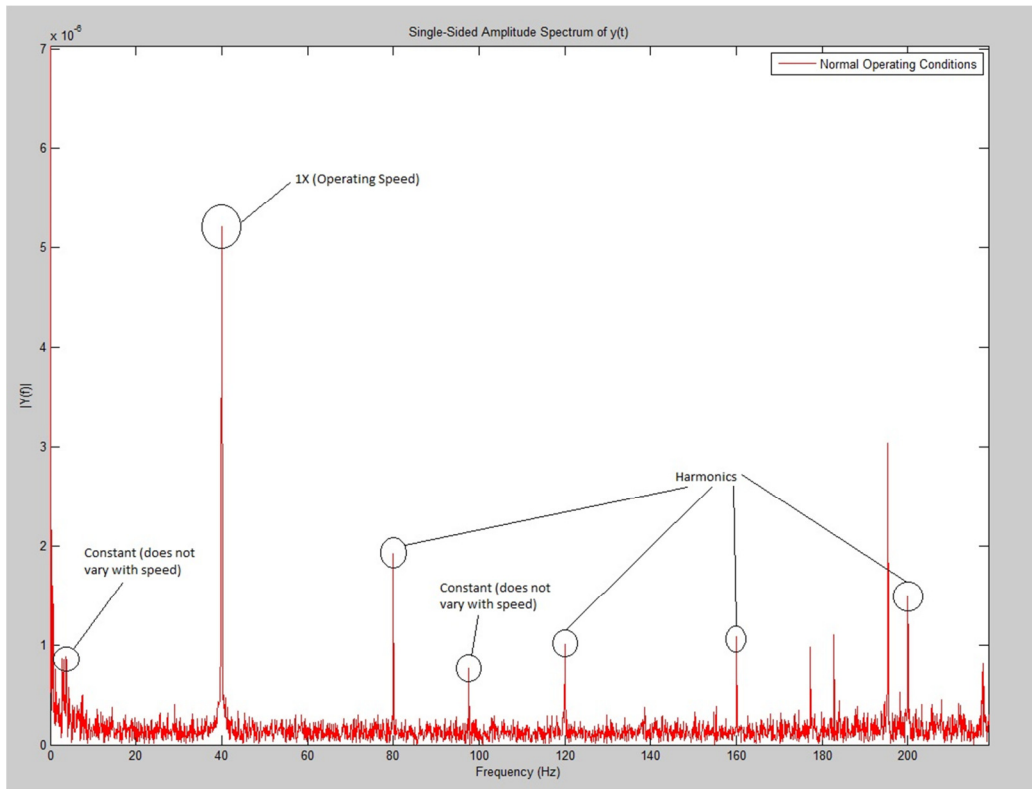


### 5.4.1 Feature Identification

As before, the first step in adapting the ANN for use in localising imbalance is the identification of nonlinearities in the frequency domain which display distinct responses depending on imbalance position across the speed range. In order to achieve this, a wide selection of data was collected and studied, with some of the resultant findings illustrated in **Error! Reference source not found..** Data was collected using a single accelerometer placed centrally on the support structure. It can be seen from this that the spectrum displays the expected 1X and harmonics, alongside two features which do not vary with the rotational speed of the machine, and some additional features between the 4X and 5X harmonics.

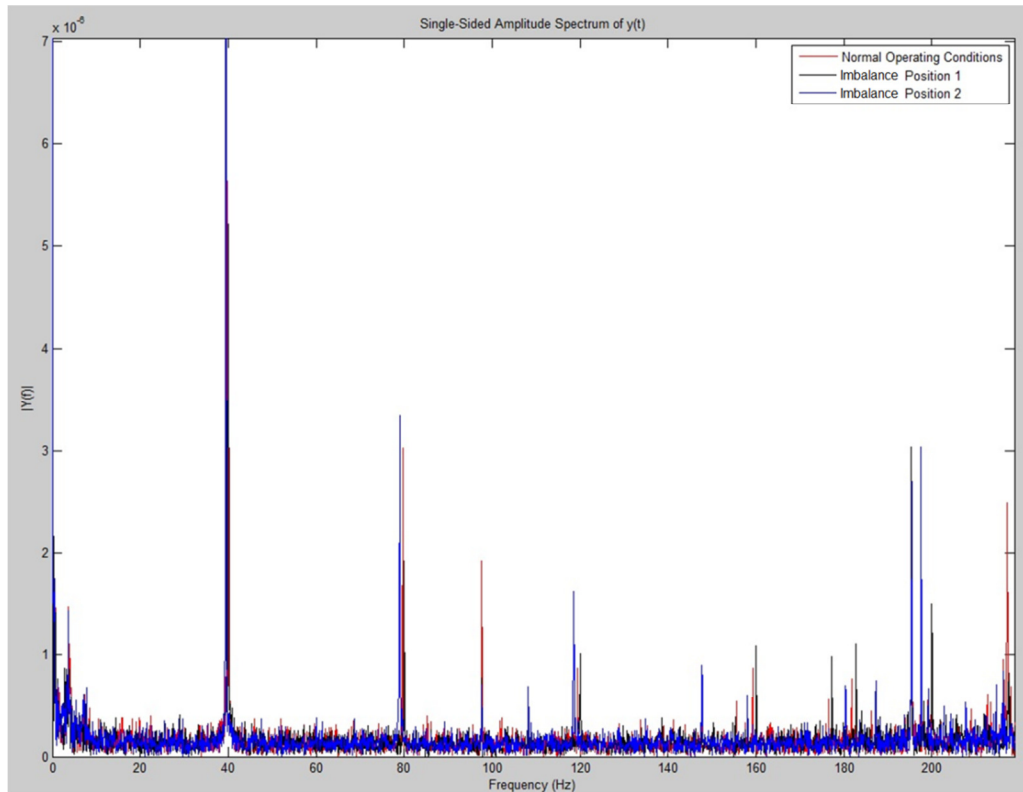


**Figure 5-9** Cranfield Balancing Rig Setup, Displaying Imbalance Fault and Sensor Placement



**Figure 5-10** Frequency Spectrum for Normal Operating Conditions





**Figure 5-11** Frequency Spectrum Comparison for Imbalance Cases

In **Error! Reference source not found.**, a comparison of three cases can be seen. Imbalance in Position 1 refers to the imbalance placed on the disc closest to the motor, whilst Imbalance in Position 2 is the imbalance placed on the disc farthest from the motor. In this case the machine was operating at a speed of 40Hz, just past the first critical speed and in the flexible regime. It can be seen that distinct peaks exist for the different cases, with particular energy releases being observed for the case of imbalance in position 2 (one example peak can be seen around 110Hz). Unlike the MFS and Technion rig, no features in the sub-synchronous regime appear to vary with imbalance position. In the case of the MFS, the nonlinearity used was tracked as occurring in the bearing. It is also suspected that some bearing feature is responsible for the 1/6X nonlinearity in the Technion rig. In this case, the oil lubricated bush bearings do not appear to exhibit such sub-synchronous behaviour. Despite this, energy

release outside of the expected harmonics has the potential to aid fault localisation.

#### 5.4.2 ANN Adaption & Testing

As with the previous studies, the first investigation of this setup involved training the ANN to look at the combined effects of the 1X-6X harmonics in order to study the ability of the ANN to predict imbalance based upon this 'linear' approach. Example results from this study can be seen as follows:

Rotor Speed	10Hz	15Hz	20Hz	25Hz	40Hz	45Hz	50Hz
Disc 1	100%	100%	95%	95%	90%	90%	90%
Disc 2	100%	95%	100%	100%	95%	90%	90%

**Table 5-5** ANN Localisation Accuracy Results for 'standard' ANN

It can be seen that the ANN achieves a good level of accuracy with this approach. This displays a partially expected response, as the two imbalance positions sit at different lengths from the corresponding bearing supports. As before, despite the high level of accuracy, room for improvement is still available. It is worth noting that vibrations due to the first critical speed result in undesirable operation of the machine between 25Hz and 40Hz. The samples for which the ANN did not return the correct result are due to the ANN confusing the two imbalance positions. In all cases, the balanced condition was successfully identified.

Unlike the two previous rigs, there does not appear to be a clear nonlinearity present in the sub-synchronous region of the frequency spectrum. However, through study of the spectrum alternate energy releases appear distinct for the different imbalance cases. In this case, a complex set of nonlinearities resolved to produce the most accurate results. As such, the input of orders to the ANN for the complex case are as follows: 1X, 2X, 11/4X, 3X, 15/4X and 4X. This series includes the dominant (1X), three harmonics of this (2X, 3X & 4X) plus

two nonlinearities (11/4X and 15/4X). The inclusion of the two nonlinear features yields the following success rates:

<b>Rotor Speed</b>	<b>10Hz</b>	<b>15Hz</b>	<b>20Hz</b>	<b>25Hz</b>	<b>40Hz</b>	<b>45Hz</b>	<b>50Hz</b>
<b>Disc 1</b>	100%	100%	100%	100%	100%	100%	100%
<b>Disc 2</b>	100%	100%	100%	100%	100%	100%	100%

**Table 5-6** ANN Localisation Accuracy Results for ‘improved’ ANN

### 5.4.3 School of Engineering Rig Testing Conclusions

The final experimental test of the imbalance localisation system has been conducted on this rig which demonstrated significant deviation in design from those previously tested. The results of training the ANN to look at differences in the integer harmonics of the speed of rotation reveal generally accurate results for imbalance localisation. However, 100% localisation success was not achieved for this case, as the ANN was unable to correctly differentiate between the imbalance position in a small number of cases.

Through the addition of non-integer harmonics, caused by apparent nonlinearities excited to different degrees when an imbalance mass is placed in a specified position; the success rate was improved to 100%. Whilst this balancing rig does not provide as much flexibility as others in terms of additional faults and multiple imbalance positions, it was possible to study a wider range of speeds. This demonstrates the potential for the imbalance localisation through the use of nonlinear features to work within both the rigid and flexible regime. In addition, unlike the other two rigs studied, this setup includes a different type of bearing. As such, it is important to note that despite the lack of sub-synchronous bearing nonlinearities occurring within the spectrum, the application of imbalance faults still produced nonlinear features within the frequency spectrum which could be used to aid imbalance. These features appear clear and distinct, dependent upon imbalance position, and can be excited by a small imbalance mass. As before, localisation has been achieved using a single, remotely placed, accelerometer.

## 5.5 Chapter Discussion

The three test cases detailed in this chapter aid in the understanding and development of the theory that machine specific nonlinearities excited by the position of imbalance faults within a system enable improved fault localisation. For the case of the MFS, misalignment and rub faults were studied. The concluding remarks from this study prescribed the use of a 'pre-screening' ANN in order to determine which faults occur within the system. If a pure imbalance is then detected, the second ANN may be run (from the same dataset) which determines the likely location of the imbalance fault. The combination of all three faults (rub/misalignment/imbalance) were found to have a complex and potentially detrimental effect on the system, indicating a potentially extreme fault case in which quick diagnosis and localisation would be desirable to prevent extensive damage. Despite the addition of other faults, it was found that imbalance localisation could still be performed with high accuracy using the nonlinear features present.

The second of the three cases utilising the Technion Institute rig proved to be an important case study. Using a very different setup from the MFS, without the  $1/3X$  sub-synchronous nonlinearity, imbalance localisation still proved to be possible through the use of machine inherent nonlinearities. Specifically, it was found that through training the ANN to use  $1/6X$  features in the frequency domain the ability to localise imbalance between two positions on the machine was enhanced. In a further development of the system, the addition of a misalignment fault enabled the validation of imbalance localisation in the presence of underlying faults. The application of this fault resulted in the ANN being adapted for run-up, run-down scenarios and introducing basic 'order tracking' to achieve this. Finally the third case enabled validation of the technique across a wide range of speeds (sub and super-critical), along with conformation that nonlinear features which aid imbalance localisation can be found in machinery without relying on sub-synchronous nonlinearities occurring from rolling element bearings.

It has thus been demonstrated that the theory of localising imbalance accurately through machine inherent nonlinear features appears to be applicable to a range of rotating machines. Within the scope of this research, this has been proven to be the case, although a number of key adaptations to the basic ANN were required in order to achieve this. These have been discussed as follows.

### **5.5.1 'Pre-Screening' ANN**

With the aim of reducing required training data and processing power, it was found that an initial 'diagnosis' phase was found to provide an efficient method in determining which faults were present within the machine. This took the form of basic use of an ANN in order to 'screen' the harmonics and nonlinearities used for localisation. As discussed in the review of literature, many methods of diagnosing differing faults have been studied, and the key features which enable this to be achieved are commonly available. In this case, the use of the ANN provided a convenient method with which to diagnose the faults in the relatively simple testing rigs. As such, in a larger, more complex rotating machine, it may be possible for a completely separate and more sophisticated fault diagnosis system to be run prior to any fault localisation system. This would require work beyond the scope of this project, encompassing much existing research. One additional benefit of this setup is the improved accuracy when localising couple imbalance faults. When the localisation ANN is 'forced' to choose a disc for imbalance (as the balanced option has already been disregarded by the 'diagnosis' stage), accuracy results return to 100%. This overcomes the limitation detailed in Table 4-5.

### **5.5.2 Run-up, Run-Down Adaption**

The localisation system required adaption for the Technion rig to operate outside of steady state conditions. This was achieved through application to a typical linear run-up, run-down scenario, with a basic method of tracking the required orders implemented. Such tests are common during engine pass-off tests, which can be important in establishing the presence of any faults before a machine enters full operation. Further to this benefit however, it demonstrates that with more complex order tracking implemented and with speed data

available it is possible to adapt the system for use outside of the steady-state conditions for which it was initially developed.

### **5.5.3 Machine Feature Identification**

The input of orders for the ANN applied to each machine varies. As the system is based upon machine specific nonlinearities, the first stage in development requires understanding of the nonlinear features across the speed range for different imbalance conditions. In most respects this is even more time consuming than training of the ANN. As such, a prior knowledge of the response of the machine and potential nonlinearities will enable the procedure of implementing the ANN to be speeded up. Therefore this is a key point for further development of the system

### **5.5.4 Rigid & Flexible machine**

It was found through testing that it is possible using this method to accurately localise imbalance faults in both the rigid and flexible regime. As some of the most commonly applied existing methods for determining imbalance rely on knowing the operating mode of the machine in order to interpret different imbalance responses, this can be seen to be an advantage of the presented approach.

## **5.6 Chapter Conclusions**

In this chapter the theory that machine specific nonlinearities can aid the localisation of imbalance was validated for a number of cases. The three tested rigs demonstrated that such nonlinearities can be seen to occur regardless of the detailed layout and specification of the machine. In all cases, the nonlinear features were found to improve localisation over a standard linear harmonic approach. In the process of achieving this, the ANN was adapted to work for run-up, run-down scenarios, and to perform imbalance localisation in the face of other underlying faults. It was also found to work in both the rigid and flexible regimes of machine operation. As such, the following chapter aims have been achieved (as published, See Appendix F).

- **Novel Aspect:** The system of imbalance localisation has been adapted for use in three test rigs, validating the theory of machine specific nonlinearities aiding imbalance localisation.
- **Novel Aspect:** The imbalance localisation system has been adapted and proven to work in the face of underlying ‘root cause’ faults, including misalignment and rub faults.

## 6 Nonlinearity Modelling and Design for IVHM

### 6.1 Chapter Introduction

It can be seen that a novel system for localising imbalance faults has been proposed and tested through experimental studies. In this chapter, the ability of the proposed system to form part of a future IVHM system is assessed through two means. As the system relies upon nonlinearities within a rotating machine in order to localise imbalance, being able to understand and predict the response of any nonlinearities to imbalance position provides an important aspect in order to consolidate the presented research. The first part of this involves simulating the nonlinear bearing effect such as that present in the MFS and assessing the responses when imbalances are applied. This takes the form of advanced modelling, building upon linear studies conducted (see Appendix). The objective of this is to demonstrate that the effect of imbalance upon machine nonlinearities can be predicted as early as the design stage. This also allows theoretical validation of the premise constructed through experimental testing to

be performed. In addition, a study on bearing nonlinearity in a full scale aircraft engine model enables the effect of bearing nonlinearities to be assessed upon imbalance position in a large, complex system.

Building upon this, a discussion centres on the ability to 'Design for IVHM'. That is, the ability to incorporate nonlinearities into the design phase of rotating machinery with the intention of enabling accurate fault diagnosis and localisation. This enables the proposed system to be presented in terms of potential development and application in the context of current research in the field of rotating machinery.

As such, the aims of this chapter are as follows:

- **Novel Aspect:** Simulate how a bearing nonlinearity such as that seen to occur on the MFS can be affected by imbalance position.
- Perform a limited study into the effect of nonlinear bearings on imbalance localisation in a full scale aircraft engine rotordynamic model.
- Discuss how the results of this indicate that the proposed system could be integrated into future IVHM systems through application with current research.

## 6.2 Model Construction & Validation

The linear studies (see Appendix) of this work provided limited information with regards to imbalance fault localisation. However, accurate models of the MFS were constructed and validated, providing information relevant to the operation of the machine. In modelling the MFS with the intent to simulate the nonlinearity responsible for bearing localisation, the models constructed in for these studies can provide a solid foundation on which to begin.

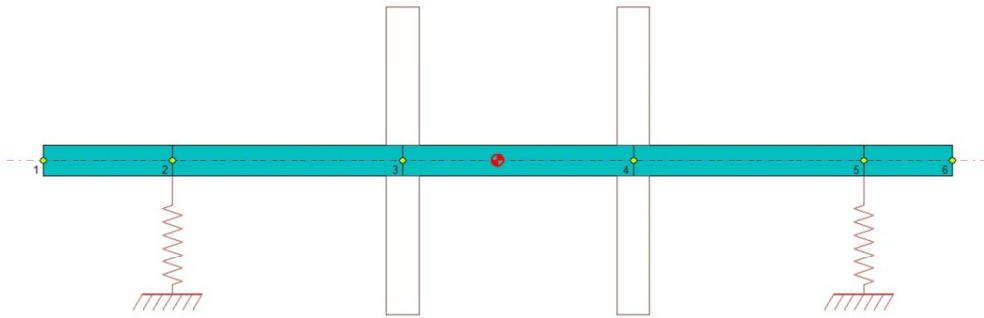
Due to the complex nature of modelling nonlinearities and the potential computational limitations (especially if modelling a full size turbine), the decision to use a specialised rotordynamic modelling package was made. For this purpose, the software DyRoBeS has been selected. The package provides a method of using finite element analysis to study rotating machinery in detail,



whilst the reduced number of elements provides for fast solutions to be obtained, without compromising accuracy in the desired areas.

### 6.2.1 Linear DyRoBeS Model

The first stage of modelling comprised the construction of a model which mimicked the Nastran high-fidelity model used for linear studies. This model can be seen in Figure 6-1.

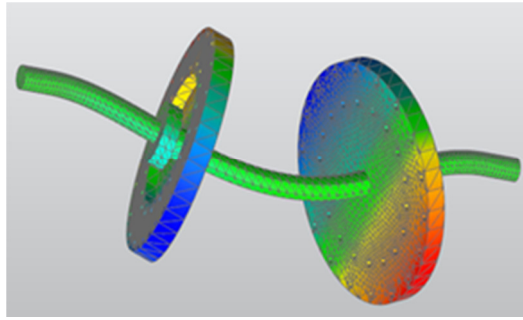


**Figure 6-1** DyRoBeS Linear Model

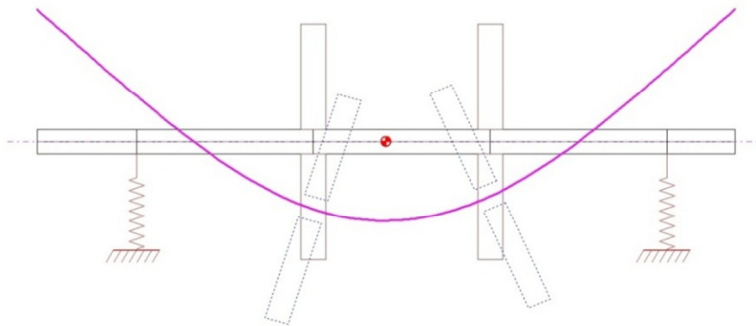
In this model, five elements are used to represent the shaft, with two linear bearings (possessing the same properties as the Nastran model – see Chapter 3) and two discs, as per the standard MFS setup. The dimensions, materials and constraints match that used for the high-fidelity models, with the intention being to validate the DyRoBeS model against the high-fidelity models (which have in turn, been comprehensively validated against the MFS).

### 6.2.2 Linear Model Validation

For the purposes of validating the DyRoBeS model, a comparison of mode shapes and critical speeds against the results from high-fidelity Nastran models has been performed. This ensures that the predicted performance of the MFS remains constant across both models. The comparison can be seen in Figure 6-2 and Figure 6-3 where the first bending and eigenfrequency are compared for Nastran and DyRoBeS models. A full comparison of predicted modes across both systems can be seen in Table 6-1 (see Appendix for further discussion of the Nastran validation).



**Figure 6-2** Nastran First Bending Mode



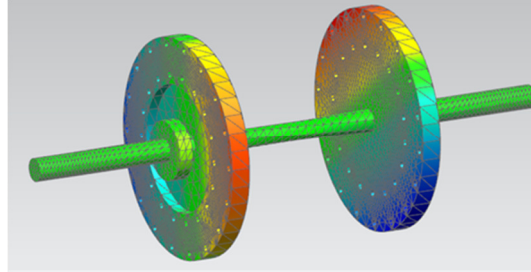
**Figure 6-3** DyRoBeS First Bending Mode

Mode Number	1	2	3	4	5	6	7	8	9	10
DyRoBeS (Hz)	112	112	160	160	359	359	582	522	634	634
NASTRAN NX (Hz)	112.4	112.4	157.9	158.0	360.1	360.1	581.8	581.9	635.3	635.4
Fixed-Fixed Hammer Test (Hz)	110	110	Not Detected	Not Detected	353	353	580	580	640	640

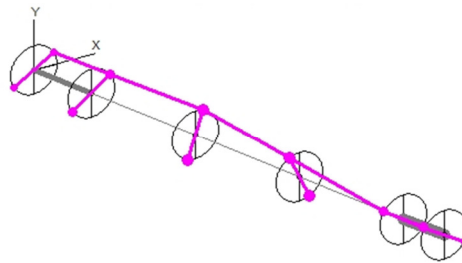
**Table 6-1** Simulation and Experimental Hammer Test Comparison

These results demonstrate the expected correlation between the low-fidelity DyRoBeS model and the high-fidelity Nastran NX model. Both of which indicate similar results to those determined through hammer testing of the structure. In this way, the DyRoBeS model can be deemed to be sufficiently validated. It can be noted that DyRoBeS displays the modes as single individual modes (as opposed to the double modes outlined in Nastran). The largest deviation between models can be seen in the first torsional mode (3-4 - Figure 6-4 &

Figure 6-5). Despite this, the models were deemed to be sufficiently accurate to allow further development of the DyRoBeS mode, incorporating bearing nonlinearities.



**Figure 6-4** Nastran NX First Torsional Mode



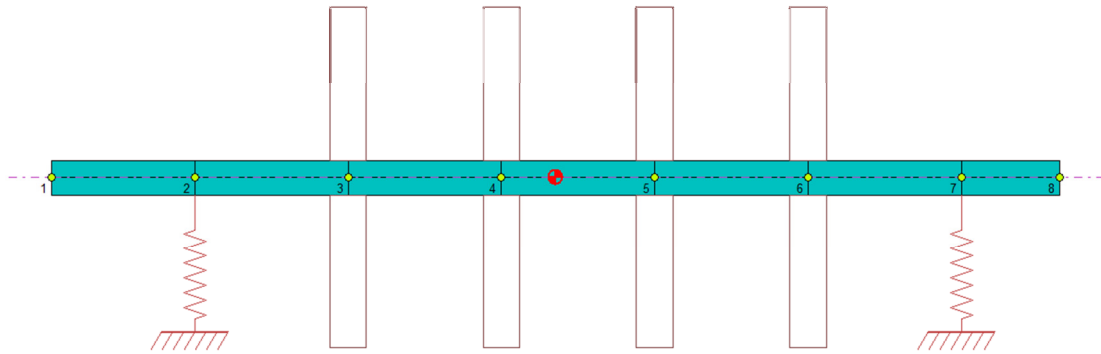
**Figure 6-5** DyRoBeS First Torsional Mode

## 6.3 Nonlinearity Modelling

The next stage in DyRoBeS modelling involves demonstrating the mechanisms behind the nonlinear bearing effects which have enabled imbalance localisation to be performed on the test rigs. Describing in detail the behaviour of nonlinear bearings, along with the effects on rotating machinery is a subject that has been covered by a number of authors, and is therefore not detailed in depth within this work. For more information on the subject, the reader is referred to the works by Worden and Tomlinson, (2001) and Yamamoto and Ishida, (2001).

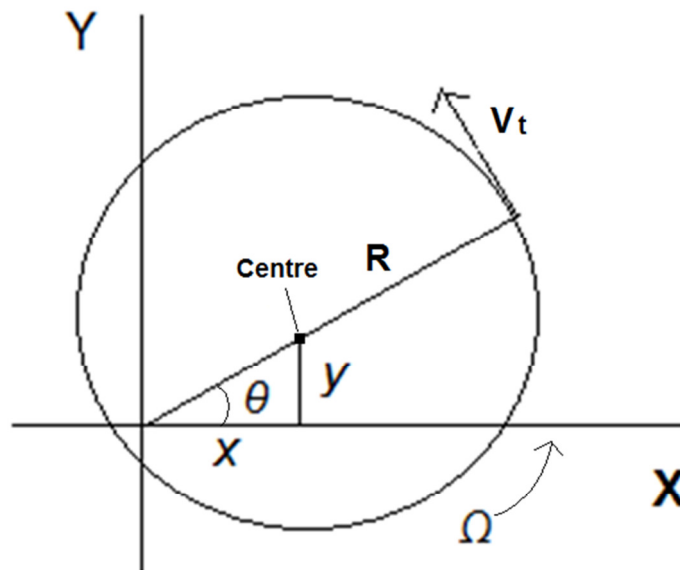
### 6.3.1 Four Disc Nonlinear Model

In order to replicate the results from the experimental studies, a four disc MFS was created in DyRoBeS, as can be seen in **Error! Reference source not found..**



**Figure 6-6** Four Disc DyRoBeS MFS Model

The two linear bearings in this model have been replaced by generalised nonlinear isotropic bearings. This specification enables a bearing clearance nonlinearity to be integrated into the model. The motion of the bearing in this case is described as follows Gunter and Chen, (2000):



**Figure 6-7** DyRoBeS Nonlinear Isotropic Bearing

Where  $(x, y)$  are the shaft centre displacements and therefore  $r = \sqrt{x^2 + y^2}$ . The tangential velocity of the shaft at the contact point is therefore given as:

$$v_t = R\Omega + (-\dot{x} \sin \theta + \dot{y} \cos \theta) = R\Omega + \left( \frac{-\dot{x}y + \dot{y}x}{r} \right) \quad (6-1)$$

The radial restoring force, where  $R$  is the shaft radius and  $\Omega$  is the rotor speed can be shown as:

$$-F_t = \mu(-F_r) \sin(v_t) \quad (6-2)$$

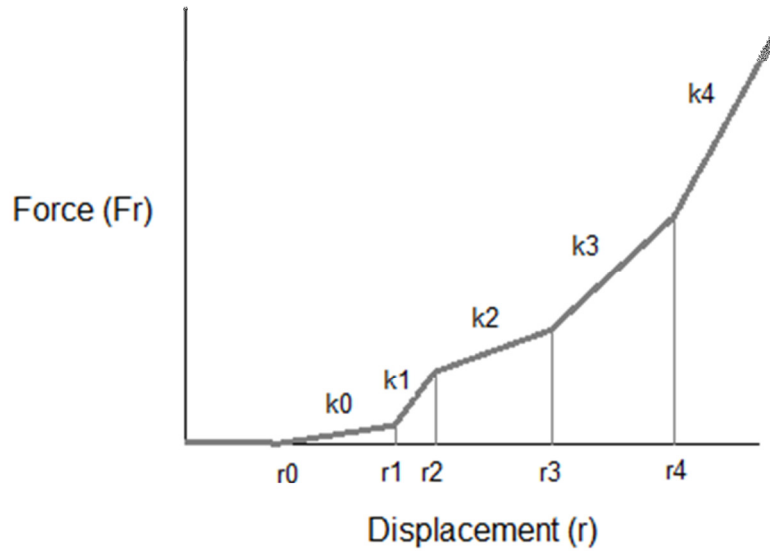
Where  $-F_r$  is the radial restoring force acting on the shaft centre due to radial displacement,  $-F_t$  is the tangential force due to Coulomb friction and  $\mu$  is the friction. The total shaft forces are therefore:

$$F_x = (-F_r) \cos \theta - (-F_t) \sin \theta - C\dot{x} \quad (6-3)$$

$$F_y = (-F_r) \sin \theta + (-F_t) \cos \theta - C\dot{y} \quad (6-4)$$

Where  $r$  is shaft displacement and  $C$  is the linear damping.

Within the model, the radial force has been represented by a bilinear piecewise curve.



**Figure 6-8** Piecewise Linear Curve

Where  $k_i$  is the slope from  $r_i$  to  $r_{i+1}$ .

When  $r < r_0$  then  $F_r = 0$ ,  $F_t = 0$ ,  $F_x = 0$ ,  $F_y = 0$ . This is the deadband or gap. In this case no forces are acting upon the shaft when shaft vibration is smaller than the clearance.

When  $r_0 \leq r < r_1$ ,  $F_r = k_0(r - r_0)$  and  $F_t = \mu_0 F_r$

When  $r_1 \leq r < r_2$ ,  $F_r = k_0(r_1 - r_0) + k_1(r - r_1)$ ,  $F_t = \mu_1 F_r$  and so on.

As a starting point, the linear values for stiffness and damping were incorporated into the model, followed by additional values for gap and friction coefficient. The final values for the bearings were determined through an extensive trial and error process. After this process testing, it was found that the following values produced results corresponding to those obtained on the MFS. As discussed, the nonlinearity varies slightly between the two bearings, allowing for the localisation of imbalance to be performed.

These values, used in the model for the two bearings, are as follows:

**Bearing 1** (Close to Motor):

Gap 1 = 0.6 mm

Stiffness 1 =  $3.8 \times 10^7$  N/mm

Damping 1 = 0.00025 N/mm<sup>2</sup>

Friction Coefficient 1 = 1.15 N

Gap 2 = 0.6 mm

Stiffness 2 = 3.8 N/mm

Damping 2 = 0.00025 N/mm<sup>2</sup>

Friction Coefficient 2 = 1.1 N

**Bearing 2** (Far from Motor):

Gap 1 = 0.5 mm

Stiffness 1 =  $3.8 \times 10^7$  N/mm

Damping 1 = 0.00025 N/mm<sup>2</sup>

Friction Coefficient 1 = 1.25 N

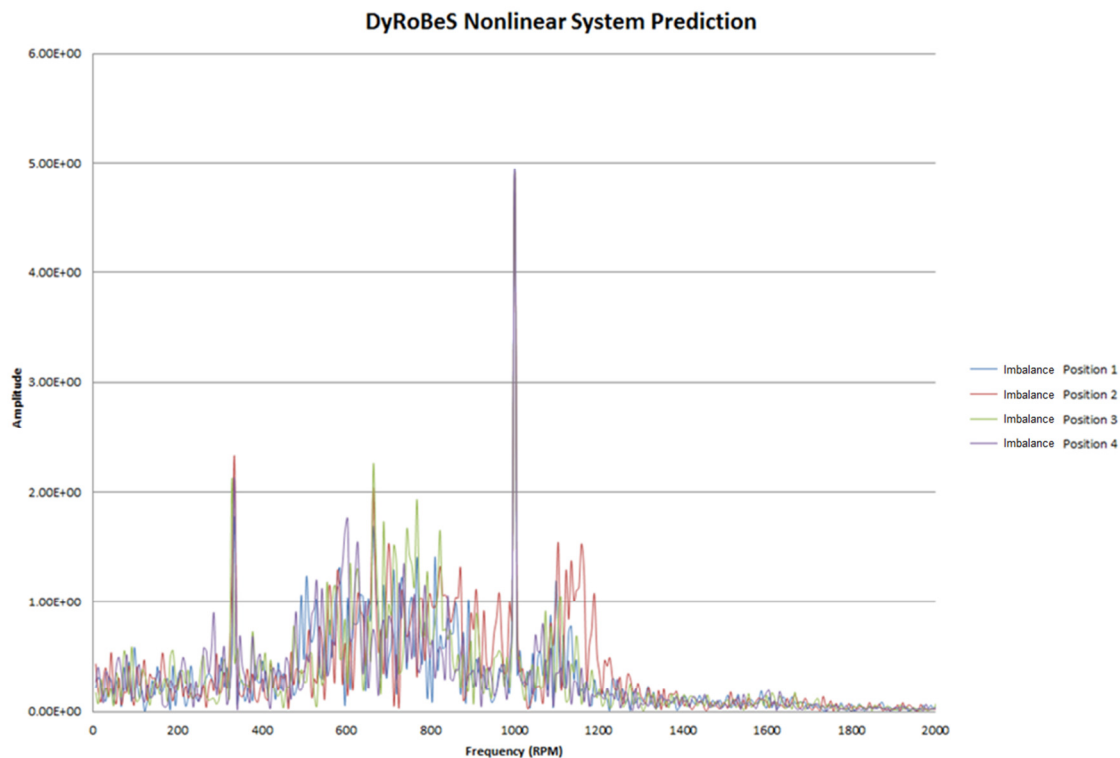
Gap 2 = 0.5 mm

Stiffness 2 = 3.9 N/mm

Damping 2 = 0.00025 N/mm<sup>2</sup>

Friction Coefficient 2 = 1.2 N

Using these bearing values, the following predicted FFT was obtained.



**Figure 6-9** DyRoBeS Nonlinear FFT for different imbalance positions

In Figure 6-9, the predicted FFT can be seen when a small (8.3g @ 70mm) imbalance is placed upon the four discs in turn (as previously, 'Position 1' refers to the disc closest to the motor, 'Position 4' the farthest). The results are calculated from the response on the motor side bearing housing. The '1X' peak can be seen at 1000rpm (the operating speed in this simulation), whilst the 1/3X peaks can be seen at 333rpm. The display shows a considerable amount of sub synchronous 'noise' consistent with the large bearing clearance nonlinearity. The amplitude of the four peak amplitudes at 1000rpm are as follows (note – values have no associated units due to being a simulated FFT):

Position 1: 4.95

Position 2: 4.92

Position 3: 4.92

Position 4: 4.94



It can be seen that they appear very similar, and it is therefore unlikely that these differences could be determined in practice on the MFS. The peak amplitudes at 333rpm are as follows:

Position 1: 1.77

Position 2: 2.32

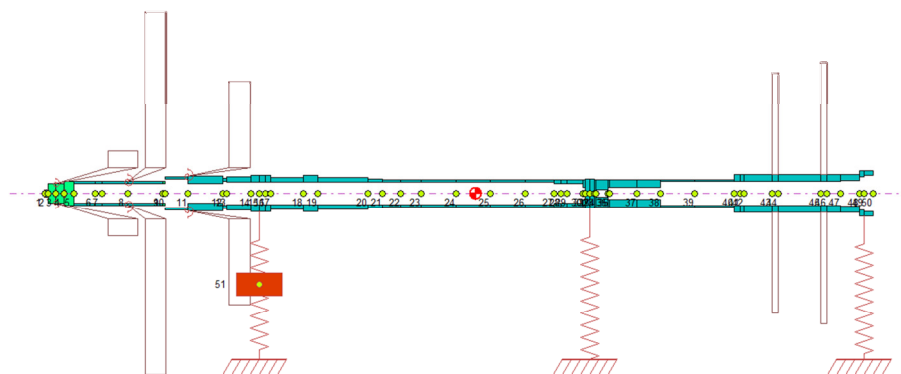
Position 3: 2.13

Position 4: 1.98

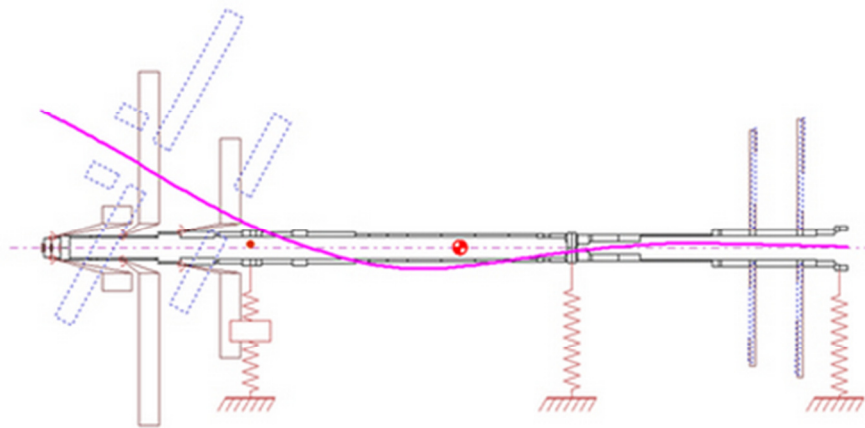
In this case, there is a larger difference between peak amplitudes, resulting in a higher probability of imbalance position detection. This result corroborates the experimental studies indicating that the nonlinear effect in the MFS enables imbalance faults to be accurately localised. It is also noteworthy from these simulations that a relatively small difference between bearing nonlinearities in the two positions appears to produce significant differences (up to 15% from above values) in sub-synchronous response.

## 6.4 Gas Turbine Simulations

In a final strand of simulation using DyRoBeS, a full size aircraft engine turbine model has been used for limited testing. This model is provided by DyRoBeS as an example simulation for critical speed analysis. The model can be seen in **Error! Reference source not found.**, and the first mode shape in Figure 6-11.



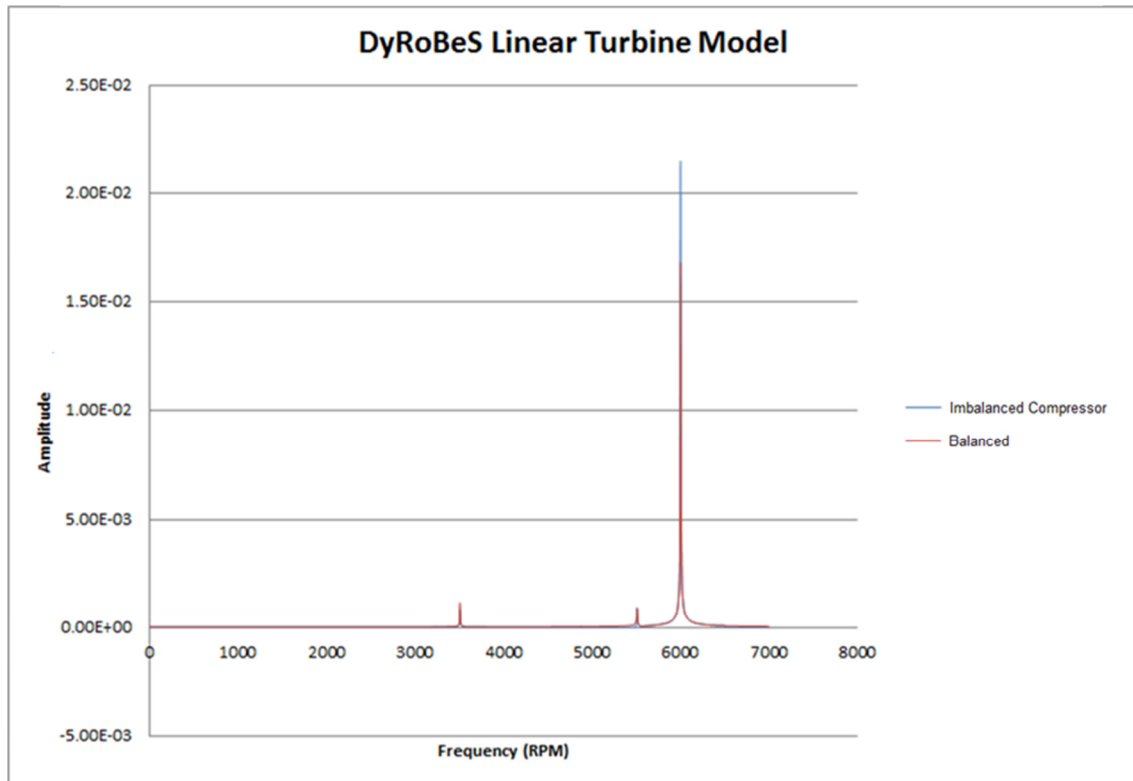
**Figure 6-10** DyRoBeS Example Aircraft Engine



**Figure 6-11** DyRoBeS Example Aircraft Engine

The authors of DyRoBeS attest to the model having been validated for testing purposes, however exact published details are not available for verification of the extent of this. Despite this, the model provides an interesting representation of a large, complex rotating machine in which imbalance localisation can be studied. The model can be seen to include three bearings, each of which holds linear values by default. The fan and compressor can be seen to the left (in **Error! Reference source not found.**) of the first bearing station. In-between the second and third bearings, two corresponding turbine stages can be seen.

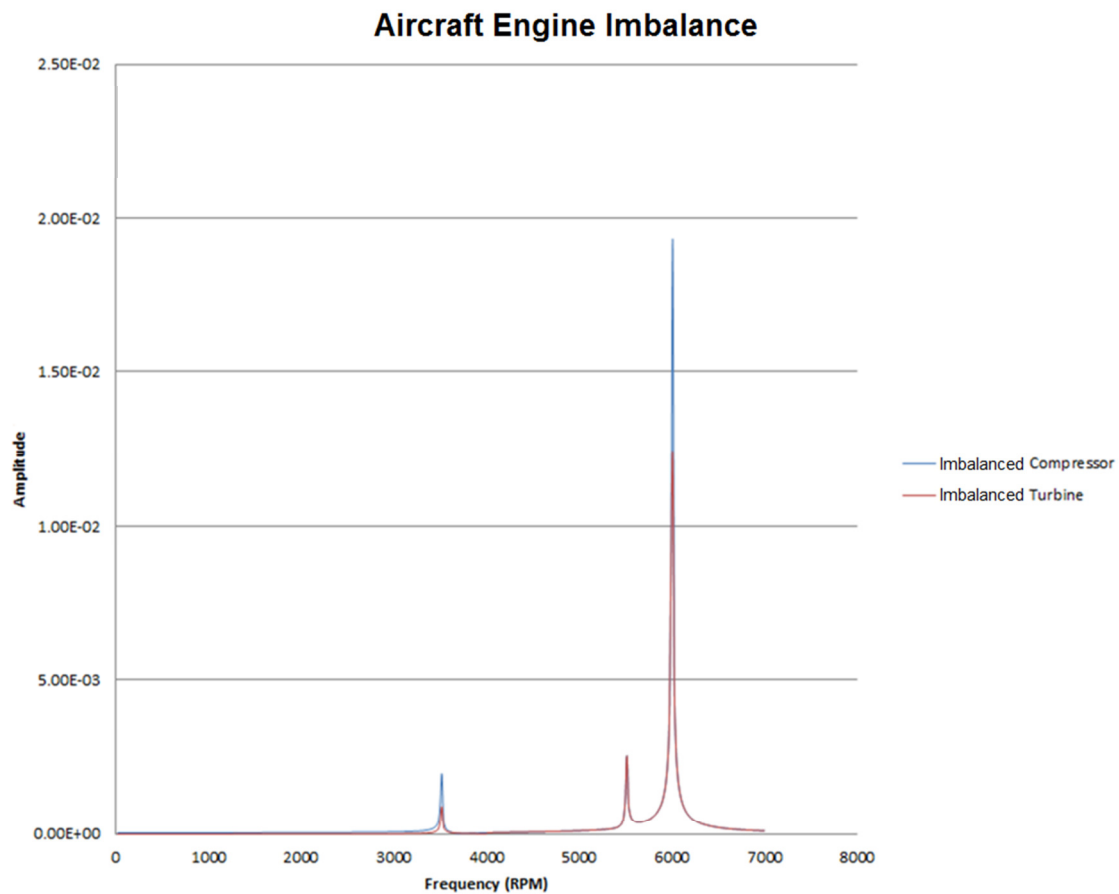
Running the model with the standard linear bearings yields the results seen in Figure 6-12.



**Figure 6-12** DyRoBeS FFT for Aircraft Engine with Linear Bearings

In this figure, two conditions are displayed. This includes balanced (normal) operating conditions, and a small imbalance added to the compressor stage. It can be seen that, aside from the corresponding increase in vibration at the 1X (6000 rpm in this figure), there appears to be no difference between the two operating conditions. As discussed in Chapter 2 and Chapter 4, relying on the 1X for imbalance localisation has inherent limitations.

Building on from this, one bearing (closest to the fan/compressor – see **Error! Reference source not found.**) was changed from linear to nonlinear, by adapting the linear values into a bi-linear piecewise curve (as per the MFS studies). This change to a single bearing was chosen as to have minimal effect upon the operation of the system. DyRoBeS predicted no significant changes to the critical speeds based upon the conversion of this bearing from linear to nonlinear. With this nonlinearity present, a study of the effects of different imbalance positions was undertaken.

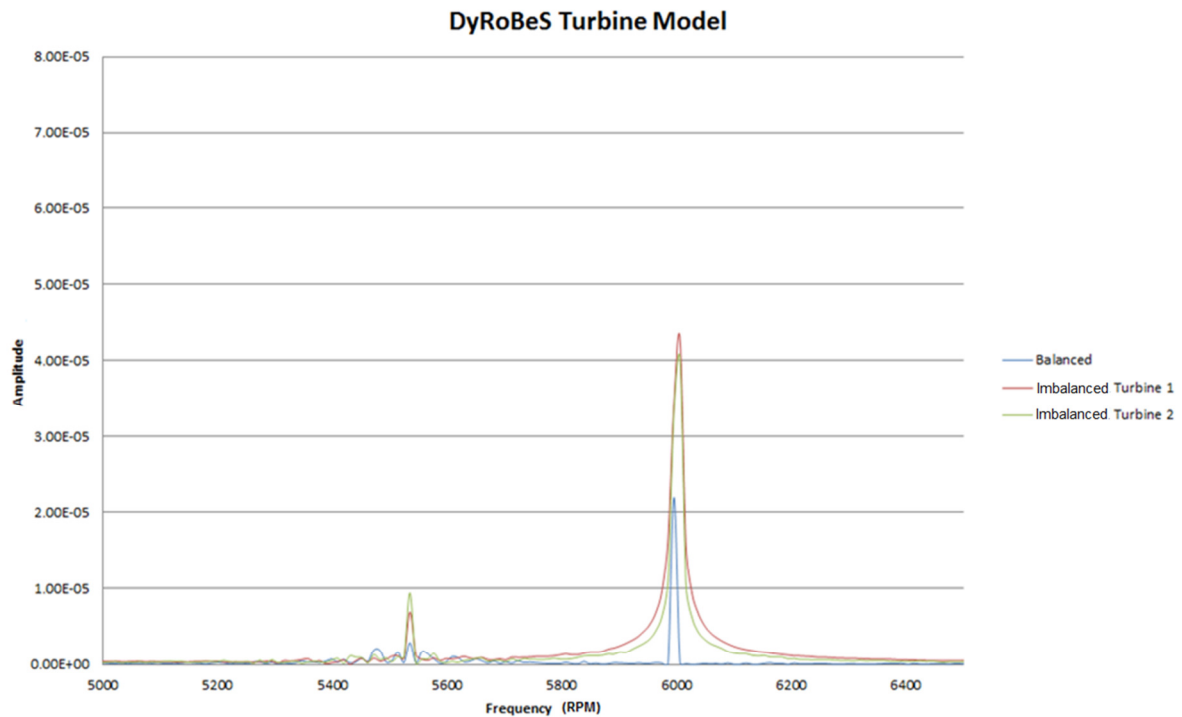


**Figure 6-13** DyRoBeS FFT Comparison for Compressor and Turbine Imbalances

In Figure 6-13, a comparison of the FFT for two imbalance conditions is shown. In this case, clear differences can be observed if the same imbalance is placed in the compressor or turbine stage of the engine. The higher 1X peak (6000rpm) occurs with the imbalance placed on the compressor. However, the nonlinear energy release predicted around 5500rpm is expected to be higher if the imbalance is placed within the turbine stage of the model. In this case, the nonlinear bearing appears to enable clear differences to be observed between the two potential positions.

Whilst it is relatively easy, given this set of conditions, to determine if an imbalance is located within the compressor or turbine stages, it is a much more complex task to differentiate imbalances within either the compressor or turbine. To illustrate this, Figure 6-14 has been created. In this case the imbalance has

been placed in turn on two turbine stages (in this simulation, both turbine discs are operating at the same speed).



**Figure 6-14** FFT of Imbalance in Aircraft Engine Turbine Stage

In this figure, the two imbalance cases appear similar. However, closer study reveals that when the imbalance is on turbine disc 1 (closest to the compressor), the 1X peak (again 6000rpm) is higher, whilst the nonlinear peak at 5550rpm is higher for the imbalance being on disc 2. This appears to indicate that imbalance may be determined to occur between the compressor and turbine stages, and even within a single stage, through comparison on the 1X peak with nonlinear energy released throughout the spectrum – as has been demonstrated through the experimental studies in Chapters 4 & 5. Whilst the aircraft engine model is simplified, and intended for the study of critical speeds (as opposed to imbalance), it nevertheless provides additional verification that the study of bearing nonlinearities enables accurate imbalance localisation to be performed.

These low-fidelity rotordynamic studies can therefore be seen to have demonstrated theoretically how the mechanisms utilised in the experimental studies function. Thus validating a number of points including:

- Bearing gap/clearance nonlinearities are responsible for the 1/3X sub-synchronous phenomena observed in the MFS.
- If these nonlinearities vary slightly between bearings, accurate imbalance localisation can be performed.
- Bearing nonlinearities may be predicted at the design stage for the purposes of informing a fault localisation system.
- This system has potential for application in a full scale turbine, subject to further testing and simulation.

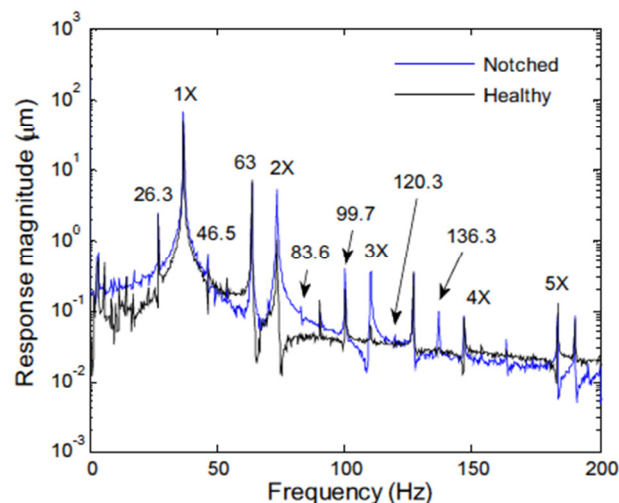
With agreement between experimental and simulation results, the validation and verification of the system can be deemed complete for the purposes of this study. From this point, discussion centres on practical application of the system, relevance to IVHM and recommendations which can be made from this project.

## **6.5 Smart Machines and ‘Design for IVHM’**

The proposed system which has been outlined throughout this research has been found to possess high accuracy in localising faults using nonlinear features, across the conditions for which it has been tested. It can be seen from the simulations that prediction of nonlinear response to imbalance position can be estimated. One fundamental requirement of the system is therefore that nonlinear features exist in order for localisation to be achieved. One current area of research which has particular potential in the context of this research is that of ‘smart machines’. This topic encompasses a wide range of research and technology intended to improve the operation of future machinery throughout extended lifecycles. Such machines have been described by Lees, (2011) to have the following ideal features:

- (a) The facility to infer their own internal state
- (b) A capability to diagnose faults
- (c) The introduction of corrective forces in the event of faults

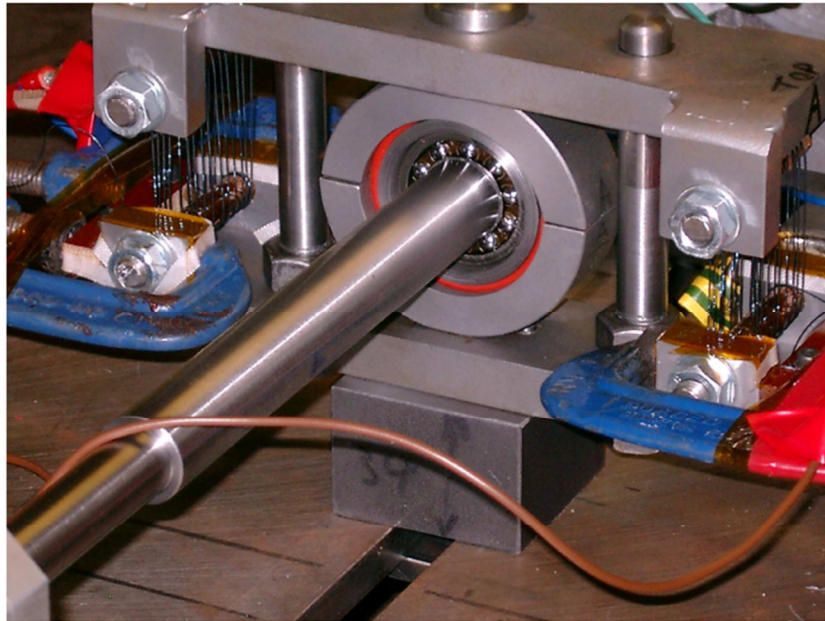
These points encompass a wide range of current research and developments; however there are some areas of particular interest to this project. One of the most developed systems available is the Active Magnetic Bearing (AMB). In a number of studies, forces injected into a rotating machine by an AMB have been utilised in order to diagnose and localise faults in rotating machinery. Sawicki *et al.*, (2008) provides one key example, whereby nonlinear forcing frequencies have been used in order to detect and localise cracked shafts. The effects of the forcing frequency can be seen in Figure 6-15, along with the clear differences between healthy and cracked shaft. The authors of this case state that “the presented approach has some merit, but further work is needed to produce a robust condition monitoring technique”.



**Figure 6-15** The Measured Response of a Damaged (Notched Shaft) and Healthy Machine, Spin Speed = 36.7Hz, AMB Frequency = 63Hz (from Sawicki *et al.*, (2008))

In addition to the approach of introducing forcing functions through AMBs, a range of alternate methods for introducing nonlinearities into rotating machinery have been studied. This includes the work by Lees, (2011) whereby application of a piezoelectric patch is studied for potential use in imbalance detection and correction. Lees *et al.*, (2007) has also extended study into how shape memory alloys can be implemented into existing bearing structures, allowing for controllable stiffness. This study is of particular relevance to the work performed

within this project, as control over bearing stiffness nonlinearities has the potential to enable even more accurate and highly controllable imbalance localisation. An image of the prototype system can be seen in Figure 6-16. A similar study performed by Majewska *et al.*, (2010) also highlights the ability of such 'smart' bearings to correct for a degree of imbalance.



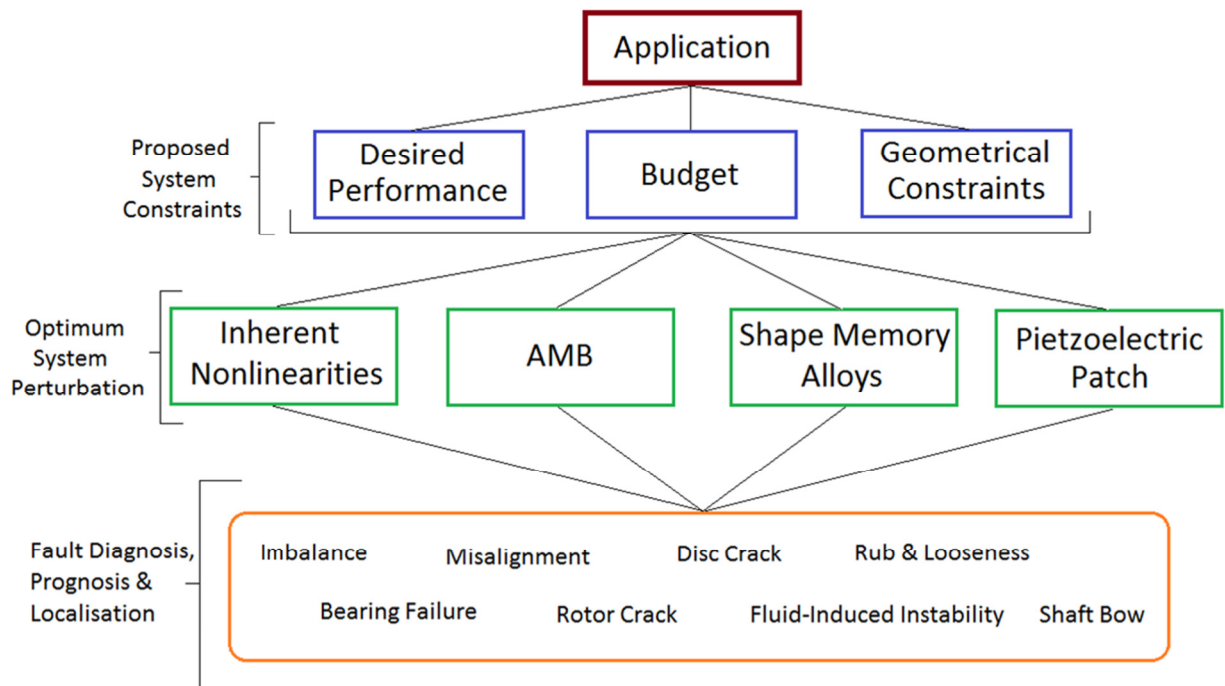
**Figure 6-16** Prototype Bearing Pedestal Stiffness Control through Shape Memory Alloy (from Lees *et al.*, (2007)).

These discussed studies on 'smart' machines do not attempt to cover the broad expanse of literature and current research on the topic. The examples provided do, however, demonstrate that the proposed method of localising imbalance has much synergy with other work in the field of condition monitoring of rotating machinery. As such, a basic example future framework for 'design of rotating machinery for IVHM', incorporating elements of the research developed here may be viewed in Figure 6-17.

Taking the basic, broad constraints of rotating machinery design, considering the desired performance (including desired lifetime and predicted maintenance requirements), geometrical constraints and the available budget, potential methods for perturbing the system can be assessed. The choice of perturbation method combined with the machine layout can then enable nonlinearities and



the responses to various rotordynamic faults to be simulated, as has been demonstrated at the beginning of this chapter. This 'Design for IVHM' approach has important implications in highlighting the advantages of the proposed system. In some cases of complex machinery, combinations of fine tolerances and noise can prevent nonlinear features from being easily identifiable.



**Figure 6-17** Incorporating Imbalance Localisation into 'Design for IVHM'

Existing research into smart machines has highlighted the wide variety of potential advantages of these systems. The research presented in this study in turn demonstrates that such machines have exciting potential for adaptation to diagnosing and localising imbalance faults in addition to cracks, and other studied faults. It is important to note that incorporating special perturbation methods specifically for localising imbalance may not be cost effective when considered as a 'standalone' system. However, when considering that the benefits of designing a machine with consideration for IVHM from the initial phases could be extensive and stretch beyond single fault diagnosis and localisation, smart machines become a promising avenue of research.

## **6.6 Chapter Discussion**

This chapter has outlined how the proposed system for imbalance localisation has relevance for a future IVHM system for rotating machinery. Firstly, development of the initial simulations to include nonlinearities and outline how imbalance position can affect the bearing clearance nonlinearity has been described. This includes validation of the mechanisms seen to occur in the MFS, along with the effects of various faults. The scaling up of the study to a basic aircraft engine model displayed the potential for nonlinear bearings to be used in such a case, without apparent significant adverse effect to the normal operation of the machine. Whilst it is acknowledged that much further study and advanced simulation would be required to fully validate this statement, the initial simulations conducted indicate positive results.

Following from this, examples of existing research have been used to discuss the potential for the proposed system for imbalance localisation to be included into next generation 'smart machines', making use of a design for IVHM approach.

In simulating a nonlinearity similar to that seen to occur on the MFS, the effect of imbalance position on the system can be 'validated' and proven from a theoretical perspective. Further to this, it can be demonstrated that such simulations allow the broad effects of nonlinear stiffness to be understood from the design phase. Combining this with examples of current research, the effect of (for example) a shape memory alloy used to alter bearing pedestal stiffness can be predicted. This allows for the response of the system to imbalance to be understood from the design stage. This, in turn, enables optimum conditions for analysing imbalance state to be predicted. Thus, a wide range of information required for condition monitoring can be estimated – from required sensor suites to optimum speed ranges for data collection.

## **6.7 Chapter Conclusions**

In this chapter, the applicability of the proposed imbalance localisation system has been studied for potential use in complex rotating machinery. This has been

achieved through the simulation of a bearing clearance nonlinearity similar to that seen to occur on the MFS, in order to observe the correlation between such nonlinearities and imbalance position. Further to this, it has been observed that such simulations could be used alongside current research into 'smart machines' for a potential 'Design for IVHM' approach to condition based monitoring. As such, this chapter has demonstrated three important points

- **Novel Aspect:** The correlation between a bearing clearance nonlinearity and imbalance position has been simulated, demonstrating the theory behind the proposed imbalance localisation system.
- The effect of imbalance position on a gas turbine model has been studied, highlighting the advantages of using nonlinearities in localisation.
- The ability for such simulation to inform 'Design for IVHM' approaches to creating future 'smart' machines has been discussed through the context of existing research.

## 7 Localising Imbalance using Future IVHM Systems

### 7.1 Chapter Introduction

Throughout this work, a novel method of localising imbalance in rotating machinery has been developed. In many published works, the development of such a system would cease at this point. However, in the context of this project it is important to consider how such a potential system for localising common faults in rotating machinery may be applied in future generations of IVHM systems.

This should include consideration of aspects which may influence the design of systems capable of diagnosing and localising common faults. The potential benefits of such a system also require discussing in the context of the costs required to achieve these gains. This chapter also enables some lessons learnt and conclusions throughout this project to be placed into context, and framed such that future research may build upon this work, rather than require 'starting from scratch'.

Some of these topics can form a substantial project in themselves, and it is therefore not possible to discuss in great depth all of the potential barriers to implementation a system such as that proposed in this research may encounter. It is, however, important to outline a framework for development which may influence further research of this and other work into localising imbalance in rotating machinery.

The aims of this chapter are therefore as follows:

- **Novel Aspect:** Develop and outline methodologies for the development of future IVHM systems for designing, locating, diagnosing and prognosing common rotordynamic faults, based upon the findings of this study.
- Outline potential 'barriers to implementation' and other considerations for the application of fault localisation in future IVHM systems.
- Use the case of the civil aviation industry in order to illustrate potential applications of the system.

## **7.2 Initial Considerations**

It is important to consider that the research presented up to this point is still at an early stage of maturity, and as a result a large amount of development is required in order to evolve the described system to a level where it can be implemented in future IVHM systems. This next evolution of the research is important in order to understand how such implementation may be achieved, and building upon this to construct a framework and methodology for imbalance localisation in complex rotating machinery. Some of these initial considerations are discussed as follows.

### **7.2.1 Sensors**

As discussed, one key advantage of the proposed system is the reduced sensor suite required for fault localisation. This is particularly relevant in industrial applications, especially in the aerospace field – where gas turbines are commonly fitted with a single accelerometer for engine vibration monitoring. In addition to the reduced number of sensors, the position of those sensors and relative transmission paths is of critical importance. Whilst for the relatively simple setup of the MFS, the described system works to a high level of accuracy, detailed knowledge of transmission paths would be required for aerospace implementation. The knowledge that the accelerometer is able to collect sufficient data of any nonlinear feature present within a wide range of operating conditions is required for successful implementation to be achieved. A number of example sensors have been used throughout the study, however a single 10 mV/g sensor proved to provide sufficiently accurate results.

### **7.2.2 Infrastructure**

In order to operate a system of imbalance localisation in a real world environment, a certain amount of infrastructure is required to be present. Whilst generally discussed in the following sections, minimal requirements include the sensor, an analogue-digital converter, and a system for data storage and easy access to the stored data. This setup enables basic access to the data when

required during maintenance procedures. In order to achieve a more advanced (on-board) system, processing and analysis requires consideration.

### **7.2.3 Analogue – Digital**

The conversion of analogue signals to digital needs to be performed on data from any sensor fitted to an engine. If using an existing engine with a pre-fitted accelerometer and access is available to this data, this requirement can be circumnavigated. However, if a bespoke system is to be fitted, this component will be required. In contrast to the system fitted to test rigs, a low-cost, durable analogue to digital converter is required.

### **7.2.4 Data Storage**

A number of potential methods of storing data exist. If abnormal (beyond a certain amplitude) vibrations are detected (indicating a fault), then a set of data may be collected autonomously in order to coincide with this. The proposed system currently makes ANN calculations based across a 20 second period of data with 500000 data points. In this scenario, capturing this amount of data across a whole flight would prove too costly in terms of storage and processing time. As the system cannot be considered mission critical (and is maintenance specific), collecting data only when required, or at set/routine points across the flight operation enables a minimum storage and processing requirement. The requirement for high frequency data capture is common when interpreting vibration data, necessitating this approach to many condition monitoring techniques which utilise vibrations as the information source. In next-generation aircraft specifically, a common data storage platform for maintenance information across IVHM technologies could be implemented.

### **7.2.5 Processing**

The processing stage potentially involves a number of complex considerations. Principal amongst these is the application and training of an ANN. Whilst it is used in the context of this research simply to summarise how such a process may be automated – and more advanced developments over the standard ANN exist in literature – the issue of training is still an important consideration. With

accurate knowledge and prediction of the behaviour of a nonlinearity (as discussed previously), changes/trends can be monitored which indicate imbalance position. However, as also noted, each machine can – although constructed to identical specifications – display a distinct vibration response. This response can change even through maintenance work (as demonstrated by the MFS). Potential methods of training an ANN include using information obtained from flight situations where the exact balance of the engine is known (e.g. initial flight after engine commissioning/overhaul). Automating the process such that these standard variations in vibration phenomena are taken into account provides one more major challenge to techniques such as that developed in this research.

#### **7.2.6 Legacy/Next Generation**

The considerations for a system differ distinctly between next-generation and legacy aircraft. In general, a system such as this may be best incorporated in next-generation systems, where nonlinearities can be designed into the initial process. Moving forward, future generations of IVHM architecture in aircraft which enable data-sharing and common infrastructure enable data to be accessed in a simpler way to the closed-loop systems currently incorporated. This leads to a fundamental consideration for the design of such a system – whether to use existing features of a system (i.e. existing nonlinearities, as described in this research) and fit a complete legacy-system, or to incorporate these considerations from the design phase.

#### **7.2.7 Different Applications**

This study draws upon examples in the civilian aerospace industry. Despite this, other potential uses exist. It can be noted from literature that the existing, linear approaches to imbalance localisation often rely upon knowledge of the mode shapes and operating regime of the system; in this case, a ‘flexible machine’. For machinery which operates purely within the ‘rigid’ regime, these techniques cannot be implemented, leading to a distinct advantage for certain applications over the nonlinear approach. As highlighted, the other potential advantage is in applications where minimal sensor suites are required. Complex rotating

machines form the basis of many systems, from aerospace to power generation, and as long as imbalance is seen as an issue, a system such as the one applied here can offer potential benefits in terms of maintenance and cost reduction.

### **7.2.8 Cost Benefit**

Quantifying cost-benefit of IVHM systems is a huge endeavour which many researchers have attempted. It is therefore beyond the scope of this research. However, it is of note that for any such system to be accepted in industry, a clear cost-benefit has to be outlined. Obtaining data on maintenance procedures and operational hours for rotating machinery can be difficult for research purposes, such data is key information required in order to quantify potential benefits of localising imbalance. Despite the absence of numbers, it can be envisaged that designing a system into an aircraft which has been fully configured from the outset for IVHM (i.e. common sensors, data storage and processing facilities) will reduce the cost of fitting such a system. If a full new data sensing, acquisition and processing kit is required to be fitted to a legacy aircraft, the cost-benefit becomes harder to justify – unless a specific imbalance issue is highlighted.

### **7.2.9 Summary of Considerations**

Building from the above main points, the following considerations need to be addressed before extensive further development on fault localisation can be performed. This includes:

- Identifying application to legacy/next generation machinery.
- Use of existing infrastructure or requirement for bespoke equipment.
- Identifying a clear cost-benefit for such a system.
- Highlight interactions with other IVHM systems to be fitted to the machine in question.
- Consideration for on/off board data processing.
- Integrating sufficient baseline data/training models into the system.



## **7.3 IVHM**

IVHM has been defined in a number of descriptions, a good summary is provided by Benedettini *et al.*, (2009), where the definitions are summarised as “IVHM [contains] a condition monitoring system that delivers value in supporting efficient fault detection and reaction planning. It offers a capability to make intelligent, informed and appropriate decisions based on the assessment of present and future vehicle condition”.

A number of important points can be drawn from this definition. It can be implied that for any system to form part of a successful IVHM architecture, sufficient ‘value’ needs to be obtained. In addition, the importance for ‘intelligent, informed and appropriate’ decisions in any implemented system can be noted. This can be described for relevance of this work in terms of the following two main benefits. It should be noted that, whilst it is envisaged that maintenance and operation provide the primary drivers for this work, in certain applications safety may also be a driver and therefore provide ‘value’. For a discussion of the role of IVHM systems in safety, see Jennions, (2013).

### **7.3.1 Maintenance**

Improving maintenance procedures is a significant potential benefit from IVHM systems. It is undesirable to work through an entire gas turbine in an attempt to determine where a fault has occurred and where the underlying cause is. Health monitoring techniques such as that proposed in this research enable significant improvements by providing technicians information required to go straight to the root cause, with minimal requirement for intrusive diagnostic techniques. Such systems can also contribute to parts availability and scheduling. If a fault can be diagnosed early as a bearing issue (for example), sufficient parts can be prepared in advance of scheduled maintenance. This opens the door for further advanced maintenance procedures, including condition based monitoring to be implemented.

### **7.3.2 Operation**

Through improved maintenance procedures, significant advances can be obtained in terms of operation. It has been highlighted that the drive for reduced scheduled and unscheduled maintenance is, in part, driven by airlines desire to operate more routes, keeping aircraft in the air as much as possible, reducing turnaround times and thus maximising profit. Improved and reduced maintenance partly enable these advances to take place. If accurate information about fault type and severity (and, ideally, prognosis) can be obtained at an early stage of development, scheduling appropriate maintenance in order to minimise machine downtime can be performed with significantly improved efficiency (Jennions, (2013)).

## **7.4 IVHM Framework for Locating Faults in Rotating Machinery**

The benefits of rotating machinery diagnostics and prognostics in next generation IVHM systems are therefore clear. In order to compress these points and the findings from this thesis into a usable format, a framework for diagnosing and locating faults has been constructed. In building up this framework, three main 'chains' have been considered.

### **7.4.1 IVHM Chain**

Central to the construction of a framework for rotating machinery is the 'IVHM' chain. This describes the key steps required in the design of an IVHM system for rotating machinery, which can in turn be achieved through the application of simulation and data-driven approaches. The IVHM chain for rotating machinery is composed of the following steps.

#### **7.4.1.1 Business Case**

Whilst outlining a comprehensive business case for the application of IVHM in rotating machinery is not an aspect that falls within the scope of this thesis, it is nevertheless important to consider the importance of constructing a valid case for the implementation of IVHM for rotating machinery. The potential benefits in accurate diagnosis and localisation of common faults has been outlined with regards to maintenance and operations within this chapter, however many more

advanced studies exist incorporating both quantitative and qualitative information. The reader is referred to Grubic *et al.*, (2009), Fan and Jennions, (2011) and Grubic *et al.*, (2011) for further reading.

#### **7.4.1.2 Design for IVHM**

Once a valid case for the implementation of IVHM systems for rotating machinery has been made, the Design for IVHM step can be taken. As described in Chapter 6, there are significant benefits in incorporating the ability to localise and diagnose common faults from the design stage, and thus this can be seen as an important step in the chain.

#### **7.4.1.3 Features**

As described throughout this work, in the fault localisation process clear features are required for the differentiation of different faults and operating conditions. This may take the form of either linear or nonlinear features, which may lie in the time, frequency or joint domains. It has been demonstrated throughout this thesis that both data-driven and physics-based approaches play an important role in feature prediction and extraction.

#### **7.4.1.4 Diagnostics**

Upon the identification and extraction of appropriate features, diagnostics (including root cause analysis and localisation) may be performed. This step includes the reasoning stage, which may incorporate physics-based and/or data-driven approaches.

#### **7.4.1.5 Prognostics**

When the type and location of any faults has been determined, prognostics may be performed with the aim of predicting the remaining useful life of all affected parts. Whilst this work has not detailed prognostics of imbalance faults, the reader is referred to Chapter 1 for a brief overview and further reading.

#### **7.4.1.6 Maintenance Decision Support**

Finally, the main objectives of the system can be realised through maintenance decision support. Knowing the precise type, location, cause and remaining

useful life can, as discussed, enable improved scheduled maintenance procedures, a reduction in unscheduled maintenance times and improved operation. Information gained from, or predicted for this stage may be fed back into the Business Case in order provide a case for the initial development of such a system

## **7.4.2 Simulation Chain**

Throughout this work, a synergy between data-driven and simulation based approaches has been described. Maintaining such a synergy in the design of a new system for fault diagnosis is an important aspect. Modern simulation tools can inform as aspects of the IVHM process for rotating machinery, and several of these tools have been demonstrated throughout this project. An indication of how the simulation chain feeds into IVHM aspects can be seen as follows.

### **7.4.2.1 Business Case**

Whilst not covered within the remit of this work, simulation has an important part to play in the construction of a business case. Modern tools including maintenance activities modelling and prioritising software enable the potential benefits of an IVHM system to be ascertained. Further information can be found in Datta *et al.*, (2004) and Swearingen and Keller, (2007).

### **7.4.2.2 Design for IVHM**

The design for IVHM stage involves extensive simulation. Anticipating modes, critical speeds and other response characteristics plays a significant role in the current design of rotating machinery. As an extension of this, anticipating any inherent nonlinearity in the machine along with a prediction of the response based upon different fault scenarios provides the basis of design for IVHM. This stage has been previously highlighted in Chapter 6, and a wide variety of simulation tools from high-fidelity to low-fidelity options enable such response predictions to be made. At this stage nonlinear actuators incorporating AMBs or similar may be included in the design if required.

Whilst the extraction of features themselves from rotating machines may be achieved through a physical sensor suite, physics-based simulation allows for linear and nonlinear features to be predicted. Such information can inform the data-driven approaches of the areas of a spectrum which useful features are likely to be obtained. This provides an important companion to the data-driven approach, potentially speeding up the process. This has been demonstrated in Chapter 6.

#### **7.4.2.3 Diagnostics**

Within this project, data-driven reasoning has been used for the purposes of diagnostics. However, the many uses of model-based approaches used by other authors, including in the domain of fault localisation must also be considered. Model-based reasoning provides a valid complement or alternative to data-driven approaches in this area, and this forms an important part of the diagnosis and localisation stage.

#### **7.4.2.4 Prognostics**

Imbalance faults can occur through a wide range of mechanisms, and therefore prognosis has not been considered in detail within this project, nevertheless the potential exists for remaining useful life to be predicted through simulation. This may take the form of FEA-based crack propagation predictions, degradation analysis on component parts through resulting rub or misalignments and other mechanisms. For details of current research in this area the reader is referred to Chapter 1.

#### **7.4.2.5 Maintenance Decision Support**

The output from the simulation chain results in qualitative information and trends which can ultimately influence maintenance decision support. The combined information providing feature prediction, model-based reasoning and remaining useful life simulation have the potential to provide, in addition to output from the data chain, a solid basis from which improved maintenance decisions can be made. The role of simulation in aiding maintenance decision

support is discussed by a number of authors, including Benedettini *et al.*, (2009) and Esperon-Miguez *et al.*, (2012a).

### **7.4.3 Data Chain**

Data-driven aspects continue to form an important aspect of rotating machinery diagnostics and prognostics, and thus continue to form an important part of the IVHM design and implementation process. Other Important aspects to this chain are discussed as follows.

#### **7.4.3.1 Business Case**

Data-driven approaches to constructing a solid business case have been discussed by a number of authors, including Esperon-Miguez *et al.*, (2012b) and Keller *et al.*, (2001).

#### **7.4.3.2 Design for IVHM**

The method by which data is to be collected for the diagnosis, localisation and prognosis of imbalance has a significant effect upon the design of a system. A potentially limited sensor suite such as that discussed in this research has, for example, significant implications upon the features which need to be identified, and potentially upon the design of a system if actuators such as AMBs are to be used.

#### **7.4.3.3 Features**

As outlined through this research, a common methodology for identifying features to be used to analysis would be as follows:

Sensor→Data Acquisition→Signal Conditioning→De-Noise→Feature Extraction

Such a data-driven approach forms a key point in the diagnosis of rotating machinery faults, with the examples used in this research detailed in Chapter 4 and 5.

#### **7.4.3.4 Diagnostics**

Once a reliable feature has been obtained, data-driven reasoning techniques may be used. Within this research, an ANN approach has been used; however

many other options are available for this purpose. Regardless of the reasoning system used, an example decision process should appear as follows:

Is the machine imbalanced? Yes/No

If yes, is there an underlying fault? Yes/No

If yes, what is the underlying issue? Rub/Misalignment/Crack

Where are the faults located within the machine?

This process has been demonstrated with success throughout Chapter 4 and 5 in this thesis.

#### **7.4.3.5 Prognostics**

The process of fault monitoring for degradation analysis provides an important counterpart to ensure that simulation based predictions for remaining useful life are accurate. A diagnosis and localisation system as detailed within this research has the potential to aid prognosis in this respect, as development of the system to track and trend any faults as they worsen could potentially be implemented. In addition, if an imbalance fault worsens to the extent that another fault is introduced (a rub or misalignment for example), then prompt identification of this enables updated prognostic simulations to be performed.

#### **7.4.3.6 Maintenance Decision Support**

As described within the research of this thesis, data-driven approaches to fault localisation may output quantitative fault information including fault types, location, underlying cause, severity and remaining useful life. If accurate information can be provided for all of these aspects, and combined with qualitative information from the simulation chain, maintenance decision support may be improved.

#### **7.4.4 Summary Development Chart**

In consolidating the information discussed throughout this chapter (and drawing upon the information gathered from the thesis), a graphical summary has been constructed. This can be seen in **Error! Reference source not found..** The

three 'tracts' can be seen, indicating the Simulation and Data-Driven approaches along with the core 'IVHM' chain. The chart can be seen to demonstrate a workflow for the creation of a system for diagnosing, localising and prognosing common faults in rotating machinery.

In addition to the three main 'tracts', some additional notes have been made on the chart. This includes the addition of the Rolls Royce 'IVHM' tracts – Sense, Acquire, Transfer, Analyse, Act. This has been displayed such that it fits in with the developed framework. The importance of the application (e.g. aerospace, marine, power) has been described to influence the business case, as well as an indication of whether the system will be next generation or legacy (retrofitted). Partitioning considerations also feed into the design for IVHM stage, and data fusion techniques may form a useful aspect of feature extraction and diagnosis. The OSA-CBM framework (described by Sreenuch *et al.*, (2012)), has also been included for the relevant stages.

Whilst it is not possible to incorporate all considerations into a single diagram, this flow provides a general guide and methodology for designing and incorporating new IVHM systems for rotating machinery, with specific relevance to imbalance localisation. If this information had been available at the beginning of the project in such concise form, the development of the described system could have enjoyed significant streamlining. Therefore, the development of such an outline enables future studies and developments to benefit from the findings from this study (both novel and summarised from existing literature). In this way, the chart describes a development methodology for localising common faults in rotating machinery, and as such presents a final novel aspect to the project, in summarising the findings for use in future work.



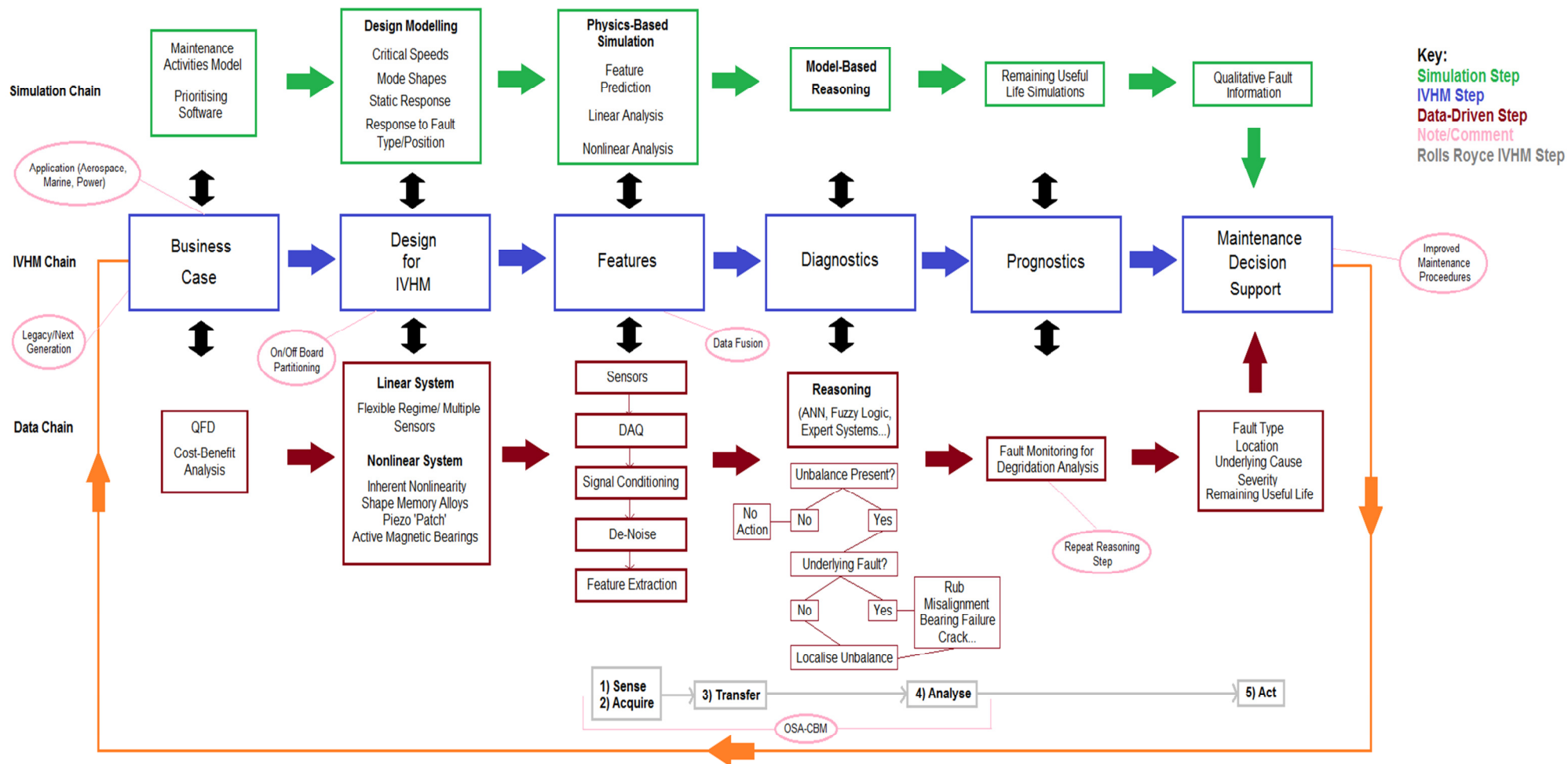


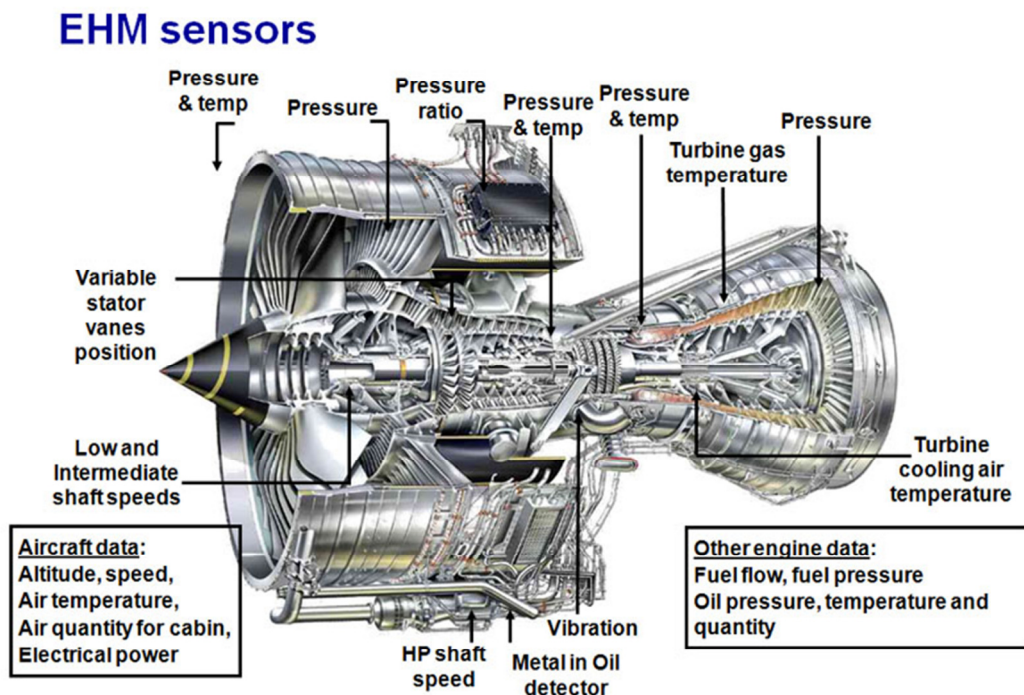
Figure 7-1 Summary Development Chart



## 7.5 ‘Case Study’ – IVHM Implementation of Novel Imbalance Localisation System

The benefits of rotating machinery diagnostics and prognostics in next generation IVHM systems are therefore clear. In order to study potential implementation of a system such as that highlighted in this research, a ‘case study’ has been considered. In this study, implementation in an off-board, off-line aerospace application is discussed. This scenario enables reduced certification requirements and cost – with minimal (or ideally no) modification to existing equipment. In this case, implementation is discussed in terms of application to legacy (already existing) aircraft. Through the discussion of a practical application, advantages and limitations of the proposed system can be highlighted. This discussion has been broken down into five key aspects, as follows.

### 7.5.1 Sense



**Figure 7-2** Location of EHM Sensors on a Rolls Royce Trent 900 Engine  
(Waters, (2009))

Existing aircraft engine turbines provide a good example of complex rotating machinery commonly fitted with a single accelerometer. In such cases, the single fitted accelerometer has a 'remote' position relative to the actual rotating parts. In the case of such machines, temperature issues prevent placement upon bearing housings, or other optimal places for detecting vibrational features. In the case of the research described for this project, a single accelerometer placed in a relatively remote position still has the potential to detect required nonlinearities. As such, for this case minimal modification would be required.

### **7.5.2 Acquire**

One potential limitation of implementing such fault localisation technology into legacy systems is the inability to access data from integrated sensors. The recent generations of aircraft are beginning to incorporate the facility to share data across systems and store larger amounts of data. In aircraft such as the Boeing 777 and 787, this integrated facility enables the potential for data to be collected which is sufficient for identifying and localising potential faults through a system such as that presented here. In older generation aircraft, such as the highly successful Boeing 737, the layout of the architecture is such that it is not possible to obtain data at a sufficient sampling rate for such a period of time, and easily store this data. As such, the latest generation of aircraft possess a much improved capacity for aftermarket modification for IVHM purposes. The acquisition system used for the novel research in this paper required small 'snapshots' of data, however tested at a high sample rate. This indicates that optimum development would be for next-generation systems, unless a large enough benefit could be determined which would cover the high retrofitting costs.

### **7.5.3 Transfer**

Another key limitation for the implementation of IVHM systems for rotating machinery is the issue of data transfer. In order to process the data off-board, a sufficient amount of data has to be transferred to a suitable ground station for processing and analysis (commonly 'operations centres' in the case of Rolls

Royce). This process typically takes the three forms. Firstly, the ACARS system – whereby a small (typically 3kb) amount of data is transferred via VHF radio and at key points of operation (e.g. take off, ascent and cruise). This system enables essential engine parameters, including basic vibration data to be assessed and trended quickly for any sign of deterioration. The limitations in bandwidth of this system, however, mean that the complex analysis required for implementation of the proposed imbalance localisation system would likely be impractical given currently implemented technology (this may however change in future - Sudolsky, (2007))

A second method is the wireless transfer of data upon arrival at certain airports. These features include Gatelink, GSM and WiFi (Brady Jr, *et al.* (2011)). These systems are not currently implemented in all airports (however it is gaining in popularity). It does, however allow for sufficient transfer of data from the aircraft to the ground for processing post-flight. The limitations of this system are, as mentioned, that it has yet to be fitted to all large commercial airports and that information cannot be obtained during flight, only after landing. However, given that the main advantages of localising imbalance faults can be found in maintenance and operations (as opposed to in flight safety) this requirement becomes less of an issue.

Finally, where the platform/infrastructure enables it, data ‘snapshots’ may be stored on board, for manual downloading by personnel only during maintenance procedures. Whilst this prevents any form of early-detection (aside from already incorporated means), it still has the potential to improve maintenance operations and, to a lesser extent, operations.

The latter two options currently appear most viable for a system of fault diagnosis and localisation, if such a system were to be developed based upon the foundations within this study.

#### **7.5.4 Analyse**

In considering the case of an off-board system, limitations in processing become negligible as long as sufficient data can be provided. If data is

transferred to external monitoring and operations centres, the application of an ANN (or alternate logic system), along with trending can be performed with relative ease and speed. In the case of Rolls Royce, ANNs are already used to interpret basic vibration data for the purposes of monitoring trends and potential degradation. In this way, fleet wide monitoring and trending can take place from a central hub, with information collated, analysed and dispatched for the purposes of maintenance. It is also important to note that only faults with a long P-F interval curve can be used for this purpose. Whilst imbalance faults may fall into this category (if, for example, a small developing crack is causing the imbalance), imbalance faults may be such that immediate attention is required. Re-training an ANN (or similar system) is likely to require flight data (as opposed to test-bed). Therefore a short period of training during which the imbalance localisation system is inactive may result after maintenance has been performed on a system.

#### **7.5.5 Act**

Acting upon knowledge the type, underlying cause and location of a fault has already stated benefits. In the case of an off-board EHM system, the benefits are slightly more limited. The pre-defined points at which data is obtained (e.g. only upon arrival at certain airports), enables longer-term maintenance operations to be planned with distinct accuracy. However, short term decisions, e.g. preparation for maintenance/inspection upon arrival of a plane at an airport, are not possible. Despite this, the ability to collect, store and trend data from a wide variety of aircraft to be collated centrally does provide several advantages. One example scenario may involve certain environmental conditions affecting engines operating at a certain global location. If this has been observed to cause imbalance issues for several engines in, for example, the high pressure compressor stage, then during the next scheduled maintenance operation for any engine operating in these conditions, this aspect can be directly investigated. This option has obvious advantages over investigating a large number of engines for any sign of imbalance across the machinery.

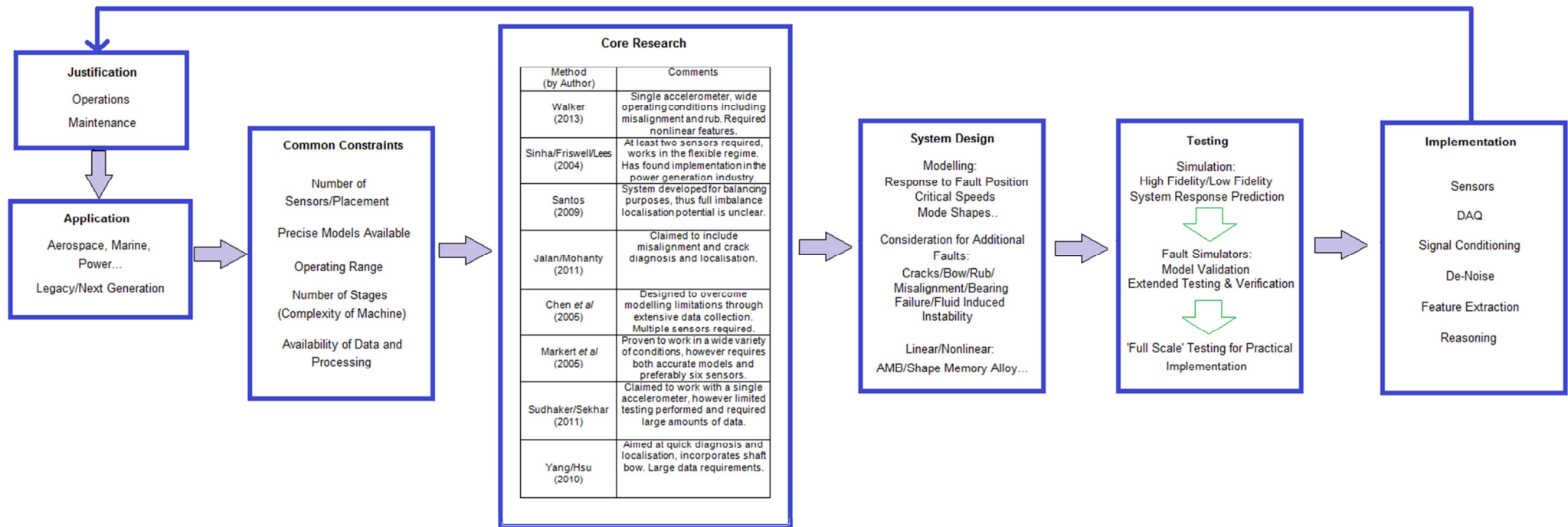
## 7.6 A Framework for Designing an Imbalance Localisation System

As a final section of work, the IVHM framework for rotating machinery and corresponding discussions has been combined with information collated throughout the research. The result of this is a final graphical methodology specific to localising imbalance in rotating machinery. Whilst simplified through necessity (as all notes and recommendations from this thesis cannot fit into a single diagram), this representation still includes key work.

Taking aspects of the literature review, modelling, experimental studies and IVHM discussion, the graphical methodology can be seen in **Error! Reference source not found..** Within this, the primary justification of improved operations and maintenance influences the application of a system. Depending upon this application, a number of constraints may be identified. Those listed are common limitations arising from the existing research (and that conducted within this project).

The 'core research' lists the 'state of the art' in imbalance localisation identified from the review of literature (along with the novel method developed in this thesis). This provides a quick 'go to' list of existing technologies. Once the core constraints and existing research is understood, a system may be designed through a synergy between data-driven and physics-based simulations. Additional testing may then be performed, as described throughout this work, making use of the latest simulations and rotordynamic rigs (before scaling up).

A typical method of implementation (as used within this research) then realises the justifications set out at the start. Through this summary chart, combined with the 'IVHM' framework, future developments in the field of localising imbalance faults for complex rotating machinery may be performed. Ultimately, it is intended that any future researchers may use this summary to good effect when undertaking such a project. As such, at this point the final novel contribution arising from this project may be concluded.



**Figure 7-3** Graphical Methodology for Design of an Imbalance Localisation System



## 7.7 Chapter Discussion

Throughout the work performed up to this point, a number of themes can be identified which enable imbalance localisation to be placed in context. It has been noted through the literature review that many imbalance diagnosis and localisation techniques which have been detailed in literature make a number of assumptions. One of these prime assumptions is that the benefit of diagnosing and localising imbalance far outweighs the costs involved. Whilst the importance of imbalance faults should not be underestimated, this assumption in many cases leads to systems which would be impractical in many real world applications. Through this research, working through a new method of fault localisation in joint consideration with the potential implementation and the ‘case study’ described, the following guidance can be highlighted for the future development of IVHM systems for diagnosing and localising common faults:

Initially, it is important to state two key points, highlighted from this research:

- A cost/benefit balance should be considered at the initial research stage.
- Application relevant constraints have a particularly significant influence on the design of an IVHM system for localising imbalance.

If these two criteria can be addressed, the following questions aid the design of a system for localising common faults:

### **General Application:**

From power generation to electric machinery and aircraft engines to vehicle turbochargers, a wide range of rotating machines exist, and their design and modes of operation can have significant impact on the type of health monitoring systems which can be implemented. Some key questions for fault localisation include:

- *Are operating conditions steady-state or variable?*
- *Is the rotor rigid or flexible? How many operational modes affect the machine?*

- *How great is the cost of machine downtime?*
- *How easily can sensors be integrated within the machine?*
- *Considering the flow Sense -> Acquire -> Analyse -> Transfer -> Act. What limitations are present within this, and where is the 'bottleneck'?*
- *How easily can benchmark/training data be acquired?*

The 'case study' highlights that within one broad application (aircraft gas turbines); a number of key limitations exist, which would render many current fault localisation systems impractical. This highlights the importance for application, practicality and cost-benefit to be considered throughout the design of IVHM systems for imbalance localisation. At present these considerations are absent from a large portion of rotordynamics research.

The final graphical methodology for designing an imbalance localisation system uses the latest published research alongside the findings from this thesis to provide a guide which is highly relevant and 'up to date' (at point of submission) for future research. This methodology may enable some of the limitations of current imbalance localisation methods to be avoided in future systems.

## 7.8 Chapter Conclusions

In this chapter, the place of an imbalance localisation system within a future IVHM system for rotating machinery has been discussed. Key concepts, limitations and recommendations are made for future developments based upon the findings from this research. The following aims have therefore been achieved:

- **Novel Aspect:** Two graphical methodologies for the development of future IVHM systems for locating and diagnosing common rotordynamic faults have been developed. These have been based upon the findings from this research, and have been illustrated together with key points and recommendations for future research.

## **8 Summary Discussion**

The final section of this work contains a discussion of all the research and related findings from this project, aimed at highlighting the novel aspects, discussing the advantages and disadvantages of the research and describing potential future research directions.

### **8.1 Chapter by Chapter**

In order to frame the work performed up to this point, this chapter begins with a short discussion of each section alongside key findings. In this way, the development ‘story’ can be outlined.

#### **8.1.1 Introduction**

At the beginning of this work, the general question of localising imbalance in rotating machinery was raised. Information from Rolls Royce, one of the world leaders in the field, suggested that the push for improved maintenance procedures and corresponding reduction in downtime will have a significant importance in future IVHM systems for rotating machinery. It was further suggested that common rotordynamic faults are still of significant concern to such manufactures, and whilst improvements in this field continue to be researched relatively little of this research finds its way to industry. Thus the general question of ‘how can common faults in rotating machinery be diagnosed and prognosed for efficient maintenance solutions in future IVHM systems?’

#### **8.1.2 Key Concepts & Review of Literature**

With the formation of a general research question, the topics for the review of literature were clear. Important rotordynamic principles were outlined alongside eight common faults in rotating machinery. These faults were discussed from the perspective of diagnosis, prognosis, localisation, modelling and common sensing methods. It was found through this review that imbalance faults are often considered to be the most common, with potentially serious consequences. Whilst imbalance faults can be potentially complex in nature,

with a variety of underlying causes, a large amount of research has been performed over the years into diagnosing these faults. The existing literature however exposed a lack of research into localising imbalance faults in complex systems. Through this finding, it became clear that improved maintenance procedures could be implemented into complex machinery if technicians have access to accurate information on not just the type, but location of the fault.

Some existing systems for fault localisation were described; however a clear gap was identified for an accurate system which could operate in both rigid and flexible systems using a reduced sensor suite. The study of published research yielded some further information that guided the direction of the study. This included the fact that a synergy between physics-based and data-driven approaches would be required, alongside indications that machine nonlinearities could play a role in imbalance detection and localisation. The importance of relating the system to next generation IVHM systems was also highlighted.

### **8.1.3 Methodology**

The information gathered from the review of literature resulted in a clear methodology being created. This set the framework for the remainder of the project, and outlined the work flow of the following chapters.

### **8.1.4 Imbalance Localisation using Four Disc MFS**

In this chapter the experimental approach to localising imbalance faults was established, consisting of the largest contribution to knowledge within this project. The recommendations from the literature were considered in order to aid the creation and development of the localisation system. The results demonstrate the potential for the effects of imbalance upon nonlinearities to be used for fault localisation. Comparison of the ‘nonlinear’ approach has been made against a ‘standard’ ANN. It is acknowledged that the ‘standard’ ANN used for comparison does not represent a state of the art approach in fault localisation. Despite this, it provides a useful indication that nonlinear features possess advantages over a linear approach, especially in the rigid regime.

The vast array of fault combinations and operating conditions available on the MFS prevented every potential combination from being tested within a practical timespan. Nevertheless, the extensive combinations of speed, sensor position and machine configuration combined with imbalance size, position and type provide a solid indication that the system can be considered validated for the MFS. Throughout this testing, the only limitations occur when a very small imbalance weight is applied. Whilst this is undesirable, the indications from the MFS are that as soon as the imbalance becomes large enough to cause undesirable vibration and resulting operations, then localisation can be performed. The difficulties in localising couple imbalance also stem from this limitation, which was in any case negated through the 'duel ANN' work in the following chapter.

### **8.1.5 Extended Testing & Validation**

The novel system developed and tested on the MFS was extended and further researched. The addition of two other rigs for testing allowed the system to be adapted with success in these applications. Through the course of this chapter, the system was developed to incorporate other faults – including rub and misalignment, operate during a run-up, run-down cycle and tested to ensure it worked with high accuracy in both flexible and rigid regimes.

The most extensive testing and validation of the system has occurred on the MFS. Whilst the other two rigs both allow for imbalance faults, as they are not designed as 'fault simulators', the combinations which can be studied are limited. However, this limitation also acted as an advantage in this case, as the two 'validation' test rigs display much smoother operating conditions. Whilst the relative size of the 1/3X feature in the MFS could almost be described as a fault in its own right (under certain operating conditions), this is certainly not the case in the two other rigs, both of which possess small nonlinearities. The two additional rigs only allow for imbalance to be located between two positions (as opposed to the four of the MFS). Whilst given the opportunity, more combinations would have been studied, even the ability to localise between two sections of a complex machine has already stated benefits.

Two additional faults were studied in this section, misalignment and rub. This was deemed sufficient to validate the localisation of imbalance in the presence of other faults. The extreme 'rub-misalignment-imbalance' combination resulted in highly undesirable (and noisy) operation of the MFS, and yet through the described method imbalance could still be localised. In future studies, the other eight common rotordynamic faults may be introduced for full validation of this statement, however the results conducted here can be considered 'proof of concept'. Whilst it is always possible to test the system under ever more complex situations, the main benefit of further work would come from application to a full scale turbine, or other aspects (see 'Future Work') which fall firmly outside of the possibilities of this initial study, and therefore at the end of this chapter the localisation system can be seen as sufficiently validated for the purposes of this thesis.

#### **8.1.6 Nonlinearity Modelling and Design for IVHM**

Having seen sufficient development of the system performed on rotordynamic rigs, in order to provide enablers for the system to be adapted to more complex systems, two further aspects were studied in this chapter. Firstly, through nonlinearity modelling the theory behind the experimentally developed system was demonstrated. This in turn enables 'design for IVHM' to be considered, whereby synergy with other existing research was considered.

The nonlinear studies have been aimed at qualitatively demonstrating the phenomena occurring in the MFS, validating the theories proposed in the previous two chapters. In this case the system appears to be successful, with differences in the 1/3X demonstrated to provide larger differences than the 1X under given conditions. In this study, quite a large nonlinear effect has been implemented in order to replicate the MFS and demonstrate the point in question, however it should be noted that this applied to smaller bearing nonlinearities as well. As a theoretical validation and demonstration of the phenomena, it was not deemed necessary to provide quantitative validation in this case for the modelling, especially as the approach described is mainly data-

driven in nature. If a 'design for IVHM' approach was to be followed however, a quantitatively validated model would likely be required.

The full scale gas turbine model provides an initial investigation into the possibilities for scaling up the system. This study is limited in nature, as full benefit is only likely to be obtained alongside practical experiments on a large turbine (or similar). The questions of "if inherent nonlinearities are present and detectable" require solving in the first instance, before extensive further modelling can be beneficial. The results nevertheless indicate positive potential for the application in such a system, if given bearing nonlinearities are present (or may be implemented). Whilst within the model, no significant adverse effects were detected by introducing a bearing nonlinearity, this would need extensive further verification if one were to consider deliberately introducing such a nonlinearity into an actual turbine. Nevertheless, the potential for this to occur is already evident, as detailed in numerous publications highlighted in the latter part of the chapter.

### **8.1.7 Localising Imbalance in Future IVHM Systems**

In the final chapter of this research, the research was placed into the broader picture of IVHM. During the review of literature, it was noted that much published research is left at the initial design stages (equivalent to Chapter 4 in this study). As the novel approach discussed in this thesis is intended to make inroads towards practical application of an imbalance localisation system, considering future constraints and requirements was deemed necessary.

The main conclusion of this chapter can be seen in the 'graphical methodologies'. Imbalance localisation is rarely discussed by authors as an issue in its own right, more as an addition to other performed work. These methodologies therefore provide a guide which represents the workflow found to be most relevant throughout this work for creating an imbalance localisation system. By framing the technical aspects (determining critical speeds, linear/nonlinear feature identification etc) alongside other considerations (business case, maintenance decision support), it is possible to calculate precisely what a proposed system must achieve. Determining such facts before

design of such a system is fully developed is crucial in order to avoid impracticalities – e.g. the system works, however requires too many sensors.

### **8.1.8 Summary of Work Performed**

It can thus be seen that the desire for improved maintenance procedures in next generation industrial applications results in the necessity for accurately localising imbalance faults in complex rotating machines. A novel system for localising these faults through application of a single sensor has thus been developed. This system has been thoroughly described and tested, performing localisation based upon machine nonlinearities. Simulation has been used alongside current research to demonstrate the potential impact of such systems in future IVHM applications.

## **8.2 The Imbalance Localisation System**

The primary contribution to knowledge within this research work is the development of a new method for imbalance faults to be localised. As this research is at an initial level of development, it is important to consider in context the advantages and disadvantages of the system along with the relevance of the work.

### **8.2.1 System Advantages**

**Single Sensor:** It can be seen that as long as the nonlinearity can be detected through the transfer path by a single accelerometer then this is sufficient for accurate localisation. In the case of the rotordynamic rigs, the limited noise enables sensors to be positioned relatively remotely and still establish the position of the faults in question. Interpolation is performed via the different nonlinear responses of the bearings rather than sensors positioned at different points on the shaft. Many current rotating machines have such limited sensor setups – including a large selection of aircraft gas turbines. Even for future systems, the operating conditions of gas turbines prevent many sensor types and positions from being used, and costs of implementation and certification result in benefits for any system utilising a reduced number of sensors. It must be noted however, that in larger, more complex systems the level of noise can



be much greater than in such rigs as tested here. This has the potential to obscure any nonlinearities that are present. Notwithstanding, current research is also on-going into new and advanced methods of noise reduction which can combat such problems. As such, this would be the topic of future research and development – however the nature of a system which uses a single accelerometer for imbalance localisation has clear benefits.

***Rigid & Flexible Regime:*** The most promising research into imbalance localisation from other authors typically relies upon knowledge of the operating mode of the machine in order to interpret imbalance position. As such, in situations where more than one sensor is available and the machine operates within a clearly flexible regime, these systems have clear promise. It has, however, been demonstrated that the technique presented within this research appears to work with a high degree of accuracy in both the rigid and flexible regime. This in turn enables implementation across a broader range of applications. This is achieved due to the interpolation of the imbalance position between bearing points. Nonlinear effects in the tested machines are different for each bearing, even if each bearing is of the same specification. Thus, the use of the operating mode and position of the imbalance relative to nodes and anti-nodes is not required for imbalance to be accurately predicted.

***Retained Accuracy with Underlying Faults:*** This aspect is an important consideration for any system for localising imbalance. As discussed, imbalance can be caused by many underlying faults or can occur as a ‘pure’ fault. Balancing a machine when the root cause is left undiscovered has the potential to lead to further failure. Relatively few published studies into rotordynamic faults consider complex chains of faults combined with localisation, and thus the demonstrated ability to detect which faults are present and then localise imbalance if required is an important and novel aspect to this research.

### **8.2.2 System Limitations**

***Nonlinear Features:*** The system which has been developed for localising imbalance relies upon the identification of nonlinearities. Whilst within the demonstrated environments the nonlinear features have been clearly

identifiable and usable, applications may exist whereby nonlinearities are not present in the spectrum due to exacting tolerances and machine design and operation. Alternatively, noise may obscure any nonlinear features in some situations. In order to fully understand the application potential of the system, further testing and development would be required. Advanced noise reduction and filtering continues to be developed, and such topics are a strong subject of research for rotating machinery. Nonlinearities in gas turbines are a particular source of current research within industry, and as such, as the understanding of nonlinear effects and filtering begin to appear, so does the applicability for systems such as that which has been developed in this research. As described, smart machinery development may also play a role in reducing this limitation. Nevertheless, the requirement for nonlinear features results in a key limitation for implementation in some machinery at present.

**Artificial Neural Network:** As has been stressed, the ANN designed and implemented for this research has been done in order to demonstrate and test the automation of the classification step. ANNs, despite the wide ranging use, have inherent limitations. Amongst these limitations is the requirement for accurate training data. In the cases described within this study, obtaining such data for faulty cases is relatively straightforward. In large, complex systems such as gas turbines it is less so. Many developments of ANNs have been described in literature, and a wide variety of alternate classification systems exist, each with advantages and disadvantages. These developments and research into AI and classification mechanisms are beyond the scope of this work, and the reader can be referred to the following works (Thatoi *et al.*, (2012) Lei *et al.*, (2008) Catal and Diri, (2009)). Whilst a ANN has been used throughout this research may not be applicable for more complex situations, for such applications more advanced classification approaches may be investigated.

### 8.2.3 Summary

It can be surmised that the system for imbalance detection and localisation contains some limitations and there is a requirement for further work in order to

develop the system for industrial application. Despite this, the system has promising advantages, and represents a contribution to knowledge in that a new method for localising imbalance faults has been determined and experimentally validated. This system is the first published example to utilise a single accelerometer in order to accurately localise imbalance cases across both flexible and rigid regime through the study of nonlinearities. The case that bearing nonlinearities can be used in order to locate imbalance has been demonstrated throughout this work. Additional contributions to knowledge include demonstrating limitations to linear FEA modelling approaches to imbalance localisation, theoretically demonstrating the links between nonlinear features and imbalance position and producing recommendations for implementation of fault localisation into future IVHM systems for rotating machinery.

## Conclusions & Contributions

Throughout this work, research aimed at advancing knowledge in the field of rotating machinery for next generation IVHM systems has been detailed. At the beginning of this thesis, the following research questions were laid out:

- Can a novel system capable of accurately localising imbalance faults in rotating machinery be developed, relying on a minimal, non-intrusive sensor suite and capable of operating under a wide range of conditions?
- How can a synergy between physics-based simulation and data-driven approaches aid imbalance localisation?
- Can imbalance localisation be accurately performed when additional faults exist within the system?
- Is it possible to create a general methodology for imbalance localisation, taking into account potential application in next generation IVHM systems?

During the course of the research, these questions have been answered as follows:

1. A novel system for localising imbalance faults has been created, based upon machine nonlinearities and using a single accelerometer. The system has demonstrated accurate results across both the flexible and rigid regimes. Testing & validation has taken place across three separate rotordynamic test rigs.
2. In this study, it has been demonstrated that physics-based simulation can be used to predict the response of nonlinearities within a system. When linked with existing research, this has considerable value for future 'Design for IVHM' systems.
3. The imbalance localisation system has been adapted and proven to work in the face of underlying 'root cause' faults, including misalignment and rub faults.
4. Taking the results and lessons learnt from this work, and discussing them through a 'case study', a general framework for localising faults in

rotating machinery has been created and outlined for use in future research.

Whilst it is acknowledged that the work outlined still requires much development in order to provide a useable solution in a practical industrial environment, the promise of the concept has nevertheless been defined. Existing imbalance systems typically rely upon the flexibility of the rotating machine and their linear behaviour. In addition to this, complex and potentially impractical sensor suits are often used. Through the approach developed within this research these limitations have been overcome, demonstrating the potential for a new method by which faults can be localised. This is of particular use in complex systems demonstrating nonlinear behaviour and with important operational requirements in the rigid regime. Whilst extensive research into both machine nonlinearities and imbalance faults has been published previously, no existing system has been created which links the two for the purposes of localising imbalance. Existing studies linking other faults (e.g. cracks) to nonlinear effects do however validate such approaches.

As detailed throughout this thesis, the following contributions to knowledge can be surmised:

### **Primary Novel Aspect**

A new method for localising imbalance faults in rotating machinery has been developed. The method uses machine nonlinearities to accurately locate imbalance faults using a single accelerometer, and functions across both rigid and flexible operating regimes. The system has been developed for use in three test rigs and in the presence of misalignment and rub faults.

### **Secondary Novel Aspects:**

During the development of the novel method, the following secondary novel aspects have been detailed:

- The correlation between a bearing clearance nonlinearity and imbalance position has been simulated. Demonstrating the theory behind the proposed imbalance localisation system (Chapter 6)
- A full scale aircraft engine model has been used to demonstrate the potential for imbalance localisation in a scaled-up system (Chapter 6)
- The study highlights some reasons why much current research into imbalance faults in rotating machinery is impractical for application in next generation IVHM systems. Key points to address this imbalance have therefore been highlighted (Chapter 7)
- Two graphical methodologies for creating an imbalance localisation system in future IVHM applications have been developed (Chapter 7)

## **Future Work**

The final section of this discussion focusses on future work. As has been mentioned throughout this document, there are many opportunities for development of the system. In this work, rotordynamic test rigs have been extensively used and tested, and as such further research on such rigs with inherent nonlinearities would not be so beneficial. Practical studies of implementation on a gas turbine have been considered, with two seeded imbalance faults within the machine. This enables the detailed study of nonlinearities, and for the research to be scaled up.

A rotordynamic rig incorporating a controllable nonlinear feature – such as those described by other researchers – combined with multiple discs for imbalance studies would also prove beneficial in extending the study to the domain of ‘smart machines’. Additional work could include investigating advanced noise reduction and AI classification methods, with the aim of reducing the current primary limitations to the system. If this selection of work proved to be a success, the relevance of the system for industrial application could be significantly improved, and as such these can be seen as the main areas for development.





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## **APPENDICES**

These appendices include work published in international conferences and journals. The papers herein include additional information supplementary to that in the main thesis body and all papers have been reviewed prior to acceptance.

### **Appendix A**

#### **Rotordynamic Faults: Recent Advances in Diagnosis, Prognosis and Localisation**

##### **Reference:**

Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, "Rotordynamic Faults: Recent Advances in Diagnosis, Prognosis and Localisation", *International Journal of Rotordynamics*, vol. 2013, 12 pages

# ROTOR DYNAMIC FAULTS: RECENT ADVANCES IN DIAGNOSIS AND PROGNOSIS

Ryan Walker, Sureshkumar Perinpanayagam, Ian K. Jennions

*Integrated Vehicle Health Management Centre  
University of Cranfield  
Bedfordshire, MK43 0AL*

## **Abstract**

Diagnosis and condition monitoring in rotating machinery has been a subject of intense research for the last century. Recent developments indicate the drive towards integration of diagnosis and prognosis algorithms in future Integrated Vehicle Health Management (IVHM) systems. With this in mind, this paper concentrates on highlighting some of the latest research in common faults in rotating machines. Eight key faults have been described; the selected faults include unbalance, misalignment, rub/looseness, fluid-induced instability, bearing failure, shaft cracks, blade cracks and shaft bow. Each of these faults has been detailed with regards to sensors, fault identification techniques, localization, prognosis and modeling. The intent of the paper is to highlight the latest technologies pioneering the drive towards next generation IVHM systems for rotating machinery.

## **1. Introduction**

The topic of diagnosing and prognosing faults in rotating machinery is an ongoing subject of research, with many developments published in a range of conferences and journals annually. This research has the potential to become even more relevant in the coming years due to the rise of IVHM, in which the drive towards condition based maintenance and whole vehicle monitoring plays a vital role. This paper intends to survey some of the recent developments in the field, with the aim of summarizing some of the more promising studies and trends with relevance to future IVHM systems for rotating machinery.

Modern day rotating machines operate with a high level of reliability, and yet the drive for ever increased operation and decreased unscheduled maintenance is providing additional challenges for industry. The airline industry provides a current example of this desire, with airlines pushing manufacturers to enable shorter turnaround times and to keep aircraft in the air longer, increasing cost benefit. Despite the high level of reliability, the rotordynamic faults detailed in this paper remain aspects which require consideration in this drive for increased reliability and improved maintenance procedures [1].

In order to fully understand and summarize the trends and developments in this area, several hundred recent conference and journal papers have been studied. Overall trends have been highlighted and discussed alongside specific papers of relevance. It is intended that the work should provide a broad reference and summary for working engineers on some of the latest developments in rotordynamic fault diagnosis and prognosis, with specific application to papers of industrial relevance for the drive towards future IVHM systems

In order to fully study the diagnosis and prognosis of rotordynamic faults, it has been deemed necessary to break down the topic of rotordynamic faults into the following sections, defined as follows:

**Sensors:** Sensors commonly used for diagnosis of specific faults.

**Fault Identification:** Diagnosis and root cause detection.

**Localisation:** Locating a specific fault within a complex system.

**Prognosis:** Prognosis of components and remaining useful life.

**Modelling:** Simulation of rotordynamic faults.

Through the study of the topics listed, it is useful to place the research conducted in this paper into context with regards to real-world applications. Further to this, it is intended to identify potential areas where more research is required in order to push some of the recent technologies highlighted for this study into industry.

Anderson [3] provides a summary of maintenance time breakdown for a collection of military aircraft. This indicates that as much as 44% of on-aircraft maintenance time (which in turn accounts for 90% of total maintenance operations) is consumed with inspection alone. The techniques addressed in this paper enable the maintenance to be more informed and targeted, with inventory ready when needed, providing a significant contribution to reducing maintenance time and cost.

As the topic of rotordynamic faults is very large area of research, the scope of this paper has to be limited. The choice of faults has been made after considering the works by Muzynska [4] and Bently [5], both of whom consider the fundamentals of common faults in much detail. Out of the wide range of possible rotordynamic faults, eight have therefore been selected. Due to the general reliability of the current generation of gas turbines, faults falling outside of the eight listed have been classed as ‘uncommon’ for the purposes of this study. This decision was made by assessing the severity of each fault, dependences on other faults and the level of research dedicated to diagnosis of each fault.

The scope of this paper is therefore confined to the following faults:

- Unbalance
- Misalignment
- Rub and Looseness
- Fluid-Induced Instability
- Bearing Faults
- Shaft Cracks
- Blade Cracks
- Rotor Bow

Each of these faults are varied, and some are more common than others. The consensus from the works reviewed within this paper is that unbalance is the most commonly occurring, in part due to the fine tolerances applied to modern machinery and also due to the links between unbalance and other faults. Misalignment can also be identified as another common fault. The particular importance of these two faults is highlighted by Domes [6] who discusses common faults from the perspective of Rolls Royce. Bearing failure is perhaps the most diverse fault here, and has the highest concentration of research in various areas. The decision has also been made to separate faults occurring on the shafts of a system to those occurring on rotors, as these can be classified as distinct faults – particularly with regards to localization and maintenance. Despite these conclusions, quantifying the faults with regards to the rate of occurrence was not possible due to the lack of commercially available data, and each of the eight faults has therefore been investigated to an equal level of detail in this paper.

It should be noted that, although the faults have been separated into eight categories they are by no means mutually exclusive. Dependencies exist between many of the faults. A common example of this is the interaction between unbalance and misalignment (outlined by Bently

[5]). Fault chains can become even more complex, misalignments leading to an unbalance which causes a rub for an example. Some works contained herein detail single fault analysis, a few refer to two or more faults. Such fault dependencies are one of the limiting factors when moving technologies from the lab into industry. An example of this would be a system capable of diagnosing unbalance faults, without consideration for misalignment as a root cause may render such a system ineffective when applied to a real world scenario.

The selected papers have been further refined based upon relevance to aero engine gas turbines and publication date (with works from the last three years preferred).

As research into the diagnosis and prognosis of faults in rotating machines is a developing topic, the application of such technologies in industry has not yet reached a stage where there are common solutions, or even a set of established procedures to follow. This holds particularly true with regards to the broader fields of IVHM. Taking the state-of-the-art Joint Strike Fighter (JSF) program as one example of the current level of technology in circulation, although the autonomic logistics proposed by Hess [7] for the vehicle is undeniably impressive, it is still a long way from implementing some of the recent technologies claimed to be successful in a lab-based environment.

Although, as mentioned, an established and commonly applied set of procedures and standards for IVHM has not yet emerged, with regards to rotating machinery a number of standards and procedures can be referred to with regards to detailing and quantifying the faults. These include such aspects as covered by ISO 2953:1999, which details correct balancing procedures and levels of mechanical vibration. Another example would be in the UK Ministry of Defence - Military Aviation Authority (2010), JAP 100A-01 - Military aviation engineering policy and regulation, where mention is made of procedures for debris and vibration monitoring. This indicates a gradual move towards common ground for procedures and standards for IVHM systems. Despite this research remains varied, and separating the research with potential for moving beyond the lab-based environment into industry can be difficult to identify at first glance.

The discussion contained herein therefore takes into account the above detailed considerations and constraints, with the aims of the paper as follows:

- Highlight key examples of the latest research in eight common rotordynamic faults
- Summarise current trends identified from the study
- Detail the current state of the art and the future work required for next generation IVHM systems for rotating machinery.

## **2. Rotordynamic Faults**

The following section details the afore-mentioned common rotordynamic faults with regard to recent physics-based simulation work and traditional data-driven methods. Research in this area of rotordynamics is particularly widespread, and so this paper outlines only a few recent areas of research. Although not of mainstream interest, a list of commonly used sensors has been included. Figure 1.1 represents a summary of the information collected and detailed as part of this review.

Faults	Sensors	Fault Identification Techniques	Localisation of Fault	Prognosis	Work of Note in Fault Modelling
Unbalance	Accelerometer Velocity Transducer Proximity Transducer	Operating Deflection Shapes Time-Frequency Analysis & Many Others	Neural-Network Modelling and Time-Frequency Analysis	FCM-Markov Model	Unbalance in Full-Engine FEA Model, Early detection in aero engines
High Radial Loads & Misalignment	Accelerometer Thermocouple Displacement Transducer Angular Sensor	Bearing Temperature Observation Advanced Software-Driven filtering methods	Various Vibration Analysis Techniques	Prognostic Modelling Using Simulated Vibration Data	Modelling the relationship between Misalignment and other faults Harmonic Balance Method
Rub & Looseness	Accelerometer Velocity Transducer Optical Sensor	Single Value Decomposition Time-Frequency Analysis	Least-squares fitting approach	Adaptive Wavelet de-noising for Prognostics	Rub & Looseness using FEA models Whole engine modelling techniques
Fluid Induced Instability	Proximity Probes Keyphase Transducer	Full Spectrum Plots Large Amplitude Subsynchronous Vibration Detection	Blade Tip Clearance and Loading Distribution	Cross-coupled stiffness and direct-damping studies	Nonlinear Modelling Accuracy of Model Based Diagnostics Numerical Modelling
Bearing Failure	Accelerometer Velocity Transducer Displacement Transducer Proximity Probes	Post-failure analysis for future failure diagnosis Dynamic time-frequency analysis	Statistical Change in the Bi-Spectral Domain	Numerical modelling of aero-engine bearings Model-based prediction of remaining useful life On-board prognostics	High and Low Fidelity Dynamic System Modelling Comparisons of algorithms to understand bearing vibration phenomena
Shaft Cracks	Keyphase Transducer Proximity Probes	Higher Order Spectra Neural Networks Grid Support Vectors	Forced Response Measurements	Non-intrusive torsion vibration monitoring	Statistical Analysis FEA Modelling
Blade Cracks	Keyphase Transducer Proximity Probes	Hilbert-Huang Transformation Model-Based Diagnostics Morlet Wavelet/Quantum Techniques	Novel Bearing Structures	Active Magnetic Actuator	Global and Local Asymmetry Modelling Finite Element Modelling
Rotor Bow	Keyphase Transducer Proximity Probes Seismic Transducer	Examination of 'Slow Roll' data Model-Based Diagnostics	Partial Mathematical Modelling	Statistical Symptoms Analysis	Advantages of Fault Modelling for Identification Nonlinear Modelling Techniques

**Figure 1.1: Rotordynamic 'Fault Table'**

As discussed, a wide selection of papers have been reviewed for consideration in this paper, of which it is not possible to describe them all in detail. In an attempt to highlight some of the common themes across many of works reviewed, the above table has been created. The table by no means details all relevant methods and approaches currently being investigated – however it details themes which were found to be common across many areas of current research. It is intended for the detailed table to compliment the important works described in more detail in the following section of the paper, separated by fault type.

### 2.1 Unbalance

This is one of the most common rotordynamic faults [5]; every rotating machine has an inherent degree of unbalance. Unbalance as a fault can, therefore, be defined as unbalance outside of a given tolerance level. A recent piece of research which demonstrates the ongoing development of data-driven techniques is that by Ganeriwala, Schwartz and Richardson [8], who tested a technique for measuring operating deflection shapes (ODS) in order to detect unbalance cases. These studies were conducted on a machine fault simulator (a physical simulator of common faults in rotating machines) – such simulators have the advantage of recreating faulty conditions quickly and easily, enabling a new dimension to data-driven diagnostic techniques. It is, however, worth mentioning that data for these experiments were collected using 14 accelerometers, which are easy to apply to such a simulator, but it may be much more difficult to configure this many sensors on a complex system. Despite this, the paper achieved its aim in proving the hypothesis “when an operating machine becomes unbalanced, its ODS will change”.

Regarding physics-based simulation of unbalance as a fault, the work by Sudhakar and Sekhar [9] described a model based method for fault identification using a minimal sensor suite. This is achieved through the analysis of transverse vibrations at a single location. Throughout the paper, three different approaches are studied – least squares minimization, equivalent loads minimization and vibration minimization. A reduced error is found to occur using a proposed

modification to the typical equivalent loads minimization approach. The work is of note due to the authors requirement to both identify and locate (localize) unbalance.

Localization and prognosis of unbalance pose a unique set of challenges and as a result, research is still somewhat limited in these areas. One recent work which claims to localise unbalance accurately is by Yang and Hsu [10], the authors use trending data and reasoning systems to locate unbalance and shaft bow across a system. Quick diagnosis is achieved by avoiding the study of all fault combinations, and the authors claim the ability to localise shaft bow and unbalance in large rotating machines. The techniques rely extensively on previous searches, and are limited to large, stable machines operating at a specific RPM. Remaining useful life of unbalance is difficult to predict due to complicating factors. As discussed, the fault dependencies are such that in many cases the unbalance itself will not be the failing factor, instead an unbalance may cause a rub which then leads to damage which can be prognoses. Such combinations of faults and underlying causes for unbalance lead to the need for remaining useful life predictions to be made based upon the exact nature of a specific fault.

## 2.2 Misalignment

This is another common fault which can potentially inflict considerable damage in rotating machines. As with unbalance, misalignment in a whole system can be complicated by secondary faults (e.g. a misalignment which causes a rub). El-Shafei, Tawfick and Mokhtar [11] is an example of the ongoing research in this area, in this case a unique combination of angular misalignment and oil whip/whirl is detailed. The authors describe how small degrees of misalignment can be utilized in order to prevent the onset of fluid induced instabilities, tested through the use of a lab based test rig. Such research presents a new dimension in looking at common rotordynamic faults, with aspects that could be applied to future design for IVHM systems.

Bahaloo, Ebrahimi and Samadi [12] demonstrate interesting research into misalignment from the perspective of physics-based simulation. The authors construct mathematical models of a simple rotor system with a misaligned coupling and collect harmonic response data from this to assess the severity of different misalignment cases. Such models are useful throughout the life of rotating machines – from design to implementation, although again successful validation with experimentally obtained data is key. The authors highlight the fact that although misalignment is a prevalent and serious fault, no comprehensive research has been performed for treating this problem. The methodology applied includes deriving the energy expressions applying the Ritz series method, constructing the equations of motion and then using the harmonic balance method to look for multi-harmonic responses. The paper demonstrates the ongoing research to understand and model the fundamentals of such faults, in order that improved diagnosis and prognosis methods can be built upon such knowledge.

As with unbalance, localization and prognosis of misalignment is a complex topic to research. Studies such as Bahaloo, Ebrahimi and Samadi [12] can make accurate predictions for misalignment in a simple system with one coupling. However, real systems (e.g. aircraft gas turbines) have many potential locations of misalignment. This is an area where few researchers have made an impact. Remaining useful life predictions for misalignment are complicated for the same reasons as with unbalance. Villa *et al* [13] discuss statistical diagnosis of misalignment faults, with reference to prognosis. The authors use the example of a wind turbine for their studies, but stress the applicability to other systems. Differentiation with unbalance faults is also covered (as these two faults are closely linked). Unlike the work by Bahaloo, Ebrahimi and Samadi [12], emphasis is given to the machine in question operating over a wide range of operating speeds and conditions. This is achieved through the use of an angular resampling method. Prognosis is tackled through the use of a statistical diagnosis algorithm based on the significance level of the faults in question.



### 2.3 Rub & Looseness

Rub is always a secondary fault (i.e. a product of another fault such as looseness) and can lead to fatigue and wear. Rub and looseness can create complex vibration signals which are difficult to diagnose using traditional methods. Modeling and simulation of rub and looseness faults have been considered in several recent works.

This includes Ngolah *et al* [14], which details the monitoring and diagnosis of common faults (including rub and looseness) based upon a three layer Artificial Neural Network (ANN). A series of 10 key performance indicators were identified and used as training. The authors test the system in a lab environment, but stress the applicability to industrial applications. The research indicates one of the latest methods of research which enables the implementation of diagnosis techniques. It is a useful tool for rub and looseness studies, as it incorporates a variety of faults which could ‘underlie’ such a fault. Despite this, the research relies on clear features for each fault, which can be much easier to identify in a lab environment as opposed to ‘noisy’ industrial applications.

Ehehalt, Hahn and Markert [15] have performed several studies into rub and looseness, including this example in which a flexibly mounted shaft has an induced rub due to a range of contact rings. The study focusses on the potentially dangerous effects of rub in causing excessive non synchronous and chaotic vibrations. The links with unbalance and misalignment are discussed and detailed. The considerations for real world cases in the described research are considerable, as part of the drive towards full understanding of the nonlinear effects of rub and looseness.

Localization of rub and looseness across whole systems is relatively lightly studied in literature. Many works (including those already cited) look at single or dual-rotor systems where localization of such faults is not an issue. In an industrial setting, complex systems may comprise many rotors in several compressor and turbine stages, significantly complicating diagnosis of such faults. Research into prognosis of rotor-stator rubs lies mostly within the domain of data-driven techniques. Modeling and simulation research can be used to support data-driven techniques for prognosis and condition-based monitoring. Han, Zhang and Wen [16] is an example of this; the authors use finite element modeling to construct a dual rotor model. Various types of rub-impact are then studied. Such studies can provide a wide range of information, which can then be combined with data obtained from live systems, potentially with seeded faults, in order to construct accurate remaining useful life predictions. As pointed out by the authors, one key advantage of simulation is the ability to study more complex systems with a higher number of rotors, which is used throughout this research. This presents a different approach to identifying features for identification of rub and looseness.

### 2.4 Fluid-Induced Instability

Fluid-induced instabilities (often referred to as whip and whirl) are potentially very serious faults which can result in wear, fatigue and extensive damage to machine components. Such instabilities can be found in interstage seals, fluid lubricated bearings and blade-tip clearances. Research into simulating and modeling fluid-induced instability has produced several works of interest to fault diagnosis of rotating machines in the last few years. De Castro, Calvalca and Nordmann [17] is a good example, where non-linear mathematical models are prepared for a rotor-bearing system. The models are then used to predict instability thresholds. The authors consider a test case against a power plant turbine and a test rig, therefore validating the simulations. The case of unbalance faults causing whip and whirl phenomena is also considered. The main conclusion therefore drawn from the work is that the authors nonlinear hydrodynamic journal bearing models enable sufficiently accurate simulations for predicting instability thresholds. Fan [18] represents an example of work from the perspective of aero

engine turbines. In this case, startup conditions are studied using a full Hilbert spectrum. The aim behind the paper is to accurately predict the point at which whip and whirl occur, thus enabling this to be avoided at the design stage. Such findings could potentially also be used to identify whip and whirl as the case of a fault after a period of wear in the operating machine.

Prognosing fluid-induced instability is a relatively lightly researched topic. Fluid instabilities can be covered as part of extensive research into remaining useful life of bearings. The potential exists for modeling and simulation techniques such as those detailed above to become a part of prognosis for fluid-induced instabilities due to the fact that it can be very difficult to seed such faults into live systems for testing and evaluation. As with other faults detailed in this report, many studies have been performed with the aim of describing fluid-induced instabilities based on the measurement or simulation of single (or occasionally dual) rotor setups. Physics-based simulation with the aim of localising fluid instability faults across a whole system can be limited by the complexity of both the fault and the system, hence, the simplification to single rotor-stator bearing systems.

### *2.5 Bearing Failure*

An area where data-driven techniques are still providing the basis of much research in the field of rotordynamics is that of bearing failure. The title ‘bearing failure’ can cover a wide range of potential issues which continue to be studied in detail. Faults can occur in all kinds of engine bearings – the inner and outer case, the cage and the rolling elements, fluid induced instabilities (addressed in a separate section), lubrication and the complexities of active magnetic bearings to name some examples. All types of bearing relevant to rotating machinery are the subject of ongoing research, and this subject has the potential to form several separate papers. As a brief highlight, some recent examples are discussed as follows. Data-driven techniques have enabled accurate bearing diagnostics and prognostics to be described for a range of rotordynamic systems. Despite the prevalence of data-driven research in this area, research from a physics-based simulation perspective has also recently produced some interesting papers of relevance to condition monitoring and health management of rotating machinery.

This includes Kappaganthu and Nataraj [19], in which rolling element bearings have been studied through the use of nonlinear models. The included nonlinearity in this case is clearance, and the model is then used in order to study chaotic motions, in particular the regions of chaotic response. The research forms part of an ongoing drive to develop an accurate model based diagnostic technique for rolling element bearings, taking into account clearance nonlinearities and chaotic responses.

Gupta, Gupta and Sehgal [20] demonstrate another example the latest research into instability and chaos in rolling element bearings through high-fidelity simulations. This detailed and complex study involves the application of a novel scheme to analyze the quasiperiodic response of the system combined with a nonautonomous ‘shooting’ method. This work highlights the level of detail to which nonlinearities and complex nonlinear motions in bearings are beginning to be understood and accurately modeled. Again, such work presents the potential for design for IVHM in future evolutions of the research.

As so much research has been performed (and is ongoing) into bearing faults across a wide variety of mechanical systems, both prognostics and localization of bearing faults have been researched in somewhat more detail than some of the other faults detailed here. Despite this, much work still needs to be performed in order to translate some of this core research into industrial applications. Research such as that detailed above has made significant advances into determining bearing failure as the root cause of a malfunction. Detecting which bearing is failing across a complex system has received somewhat less research. Bearing prognostics is another area with much ongoing research being performed – both in the simulation and data-

driven domains. To give an example, Hong *et al* [21] combined grade life and extensive mathematical modeling techniques in order to produce prognostic models for aero engine bearings. The results are described by the authors as ‘practical and verifiable’. Although a number of similar recent studies exist, this work is of note for the extent of the studies performed which include bearing test stand run-to-failure validation. The lab results appear impressive, this research has yet to be applied and tested in real life applications – indicating that, despite the number of parameters considered it is still not possible to model naturally occurring phenomena sufficiently.

A large body of work in this area also exists from Randall and Sawalhi [22], where several examples of data driven techniques can be seen applied to a wide variety of bearing types. An example of recent developments involves the use of ‘cepstrum pre-whitening’ in order to remove sufficient noise for accurate bearing diagnosis and prognosis. This work is particularly noteworthy due to the emphasis on real world applications, where the traditional lab based techniques of order tracking and synchronous averaging do not provide sufficient noise removal for harsh industrial environments. The addition of such techniques is a crucial step in developing the current generation of diagnosis and prognosis algorithms for use in future IVHM systems.

## 2.6 Shaft Cracks

Another potentially serious fault in rotating machinery is shaft cracks, and so early detection of any such fault is highly important. Methods of crack formation and propagation can be diverse, and range from high and low-cycle fatigue to stress corrosion. Simulation and modeling of shaft cracks can have significant advantages over data-driven methods. Perhaps the most obvious advantage is the relative simplicity of inserting a fault into, for example, a finite element model as opposed to seeding a fault in a working industrial machine. As such, research into shaft cracks has been progressing steadily with the corresponding increases in computing power.

A clear synergy between data-driven and physics-based simulation research can be implied by a number of recent works of research. An example of recent advances from a data collection perspective is Li *et al* [23], which details statistical models based on historical data for condition monitoring purposes. This unique work uses the human auditory system as inspiration for enriching methods of mechanical faults and features extraction. The results indicated by the paper are perhaps not as convincing as some other methods discussed in this paper, it describes an interesting ‘outside the box’ method of tackling common problems.

From a modeling perspective, Bachschmid *et al* [24] cover a wide range of vibration phenomena in order to develop a model based identification and severity procedure. This work is noted for its thoroughness in modeling procedure, including accurate modeling of the crack breathing mechanism. A combination of high and low fidelity models are validated through experimental study, and ‘excellent’ accuracy is claimed by the authors in detecting crack position and depth through the use of the proposed model based diagnostics.

The nature of shaft cracks has resulted in a wide variety of research being performed into both localization and prognostics of these faults (indeed, the two topics can be considered related). Recent examples of work in this area include Karthikayan, Tiwari and Talukdar [25], which details crack localization using forced response modeling. In this case, a test rig was constructed consisting of a circular shaft supported by two bearings. Frequency-domain data was used to create a localization algorithm, designed in combination with an FE model. Although this research provides good accuracy of localization in a lab environment, it remains untested in a more complex system (e.g. a full gas turbine).

Inoue, Ngata and Ishida [26] describe finite element modeling of crack propagation, with validation against experimental results provided to demonstrate the validity of such modeling

techniques. The paper concentrates on natural frequencies and resonance curves. Whilst the authors claim improvements in the ability to understand such faults, again the system in question is quite simple – and such FEA models are difficult to scale up to full size applications.

### 2.7 Blade Cracks

Blade cracks, if allowed to develop, can result in serious consequences. Cracks can form due to high centrifugal stresses across operational cycles (in the case of an aircraft gas turbine, for example, start up and take off through landing and taxi). As excessive crack growth can lead to catastrophic rotor/blade failure, early detection and prognosis of such faults are essential. As with shaft cracks, physics-driven simulation of blade cracks is an area of significant research. This varies from high-fidelity finite element models to low-fidelity system and mathematical models. The recent work demonstrated by Green and Casey [27] is a good example of recent mathematical modeling from a diagnosis perspective. In this paper the authors concentrate on early detection using global and local asymmetry crack models. 2X harmonic components are identified as key areas for the early detection of blade cracks, however again this paper suffers from being applied and tested on a relatively simple system which may not scale up to a full size turbine.

Inoue, Ngata and Ishida [26] demonstrated high-fidelity modeling, the authors used FEA to model crack growth, making comparisons and validating against an experimental rig. This work is particularly interesting as it outlines the advantages and drawbacks with the latest state-of-the-art modeling techniques.

Localization and prognosis of blade cracks have also benefitted from recent advances in simulation and modeling. Sawicki *et al* [28] contains details of work on a novel active magnetic bearing system for use in the early detection, localization and prognosis of blade cracks. Again the emphasis is on early detection, with the bearings used to excite the system in order to obtain optimum response vibrations for analysis. The authors admit the approach has some merit in diagnosing blade cracks, however it is in the early stages of development and work is ongoing. FEA has also been used extensively to support blade crack prognostic tools; Xiang *et al* [29] is an extensive example of recent work. In this case, a number of advanced FEA methods are applied to produce accurate FEA solutions – these include surface-fitting techniques and the contour-plotting method. The authors experimentally validate their work and suggest that it can be applied to prognosis and quantitative diagnosis of blade cracks. Despite the claimed advances, again the scalability of such research to full size turbines is an issue – particularly with regards to the complexity of the FEA models.

### 2.8 Rotor Bow

Rotor bows can be a primary source of unwanted vibration in gas turbines. The main cause of a rotor bow (rotor bows do not include bows due to gravity) are thermal differences in a system caused by operating conditions. It is noted by Domes [6] that this non-symmetrical thermal distribution can cause excessive unbalance to the extent where a gas turbine will not start correctly. Such rotor bows are common on start up or shut down, and are often accounted for in operational procedures. However, if thermal ‘hot spots’ exceed a given tolerance level, they can cause permanent unbalances due to rotor deflections. Such rotor bows can lead to other faults, including rubbing and looseness which complicate isolation and localization.

Traditional data-driven techniques for detecting rotor bows involve combinations of slow roll and vibration data [30]. More recently, mathematical modeling techniques such as that detailed by Meagher, Wu and Lencioni [31] have been used in order to diagnose residual rotor bows, and differentiate these faults from other sources of unbalance. The authors of this

paper build upon established methods for the models, and are unique in that they concentrate on response at the bearing points. This is perhaps more useful for industrial applications, as vibration information is more readily available at bearing points rather than intrusive proximity probes, which are often used in lab work.

The little work that exists on attempting to localise rotor bows across complex systems tends to be data-driven in nature; see Galka and Tabaszewski [32] where the authors used statistical symptoms based on known data as a method of diagnosing and prognosing a number of faults, including rotor bows and unbalance. This paper attempts to address the irregularities and fluctuations that occur over a long service life. In order to achieve this, a modified energy processor model is created, using data drawn from large steam turbines over long periods of life.

Prognosing rotor bows is a complex subject. As rotor bows are often caused by temperature deflections, making predictions for remaining useful life and potential future problems lies not only in the realm of mechanical rotordynamics but also to some extent in thermodynamics. The recent work detailed by Sinha [33] is of note for detailing diagnosis and quantification of various rotordynamic faults and describing the advantages of mathematical modeling over traditional vibration-based approaches. The topic of scalability regarding FEA models is discussed, including an argument for the use of partial (simplified) mathematical models for large, complex systems.

Another two works which are of interest with regard to modeling of rotor bows include Shen, Jia and Zhao [34], where the authors modeled a rotor-bearing system with a permanent rotor bow, looking at the impact of secondary faults such as rub. The study of fault combinations in this paper is useful for fault differentiation studies; however the authors study a permanent, initial rotor bow. This therefore does not take into account developing or worsening faults and the different vibration phenomena that are observed as such faults are developing.

Lees, Sinha and Friswell [35] describe the importance of model-based fault identification techniques and outlines recent research in the area, providing a good reference paper for more research on this specific fault.

### **3. Discussion**

#### ***3.1 Sensor Suites***

The subject of sensor suites is of great importance with regards to future industrial applications. On one hand, advanced and complex sensor suites generally enable improved fault localization and diagnosis – however the added complexity and cost has resulted in many of these systems being omitted from the latest generations of rotating machinery in industrial applications. From an industrial perspective, the cost benefit of additional sensors needs to be significant in order to justify this approach. In response, a number of works listed, including [9] as a good example, take the approach of achieving the same objectives using a greatly reduced sensor suite. In many ways, the required sensor suite for many of the currently researched fault diagnosis and prognosis techniques provide an indication of the ability of the techniques to be used practically in industrial situations. A complex suite may return a very high success rate on a lab based rig, however the impracticalities of mounting such suites on a real world application negate the advantages.

Further to this, the consideration for sensor position must be considered. The use of proximity probes and keyphasor transducers have very clear advantages in a number of situations – however the intrusive nature of the sensor prevents application in a number of complex systems. With this in mind, a number of the more promising studies listed rely on the simple suite of an accelerometer placed in positions which are relatively remote from the sources of vibration, potentially with a noisy transfer path.

### *3.2 Diagnosis*

It can be seen from the research outlined in the previous section that the diagnosis of faults in rotating machinery is a subject of much ongoing research. This involves the improvement and development of traditional vibration monitoring techniques, development of new data-driven technologies and novel research into physics-based simulation and modeling. In many cases, these topics of research are dependent on one another for reasons of validation, verification and speed of analysis. In several cases, it can be seen that multiple faults have been modeled for the purposes of identification and isolation. However, no studies have yet been performed which deal with all of the afore-mentioned faults. All of these faults are intrinsically related to one another. Complex combinations of faults have begun to be analyzed with the emphasis on developing new diagnosis techniques. Physics-based modeling has proven to provide significant advances with regard to specific faults, notably shaft and blade cracks, where techniques such as FEA enable much easier, faster and cheaper test data then seeding faults into live systems.

It can be noted, however, that both high and low-fidelity modeling techniques are being applied to cutting edge research for all of the listed rotordynamic faults (and others not detailed in this paper). In addition to the advantages in the speed of obtaining test results, physics-based simulation is providing another dimension to data-driven techniques. System models are being used as part of logic and reasoning suites in the identification and differentiation of various faults. High-fidelity models enable simulations of fault combinations which it are not possible, practical or are prohibitively expensive in live systems.

Nevertheless, results obtained from modeling studies still need to be validated against proven data-driven techniques before implementation in industrial applications is possible. It is also of note from the literature reviewed for this paper that almost all modeling for the diagnosis of faults involves extensive simplification, often reducing potentially complex systems down to one or two disc/shaft/bearing models. Adapting the claimed results from such research to systems with many discs/bearings/shafts is important in improving existing rotating machinery diagnostic techniques.

The inclusion of nonlinear effects is notable amongst many authors – as the understanding of the complex faults and interactions continues to progress. Such research opens the potential for promising new avenues into areas of design for IVHM.

Finally, it is of note that despite the wide variety of advanced research here, a consensus for the most efficient techniques and algorithms has yet to emerge in order for the final adaption to industrial application to be achieved. However, the consideration for industrial application taken by many of the authors detailed in this paper provides promise for next generation IVHM systems.

### *3.3 Localisation*

Fault localization in rotating machinery is an important topic of research for future condition-based monitoring systems. Knowing not only what type of fault has occurred, but also where in the system is an important consideration which can influence maintenance procedures in complex machinery. It is worth noting from the literature surveyed for this paper that many studies have focused on diagnosis and prognosis of single rotor/bearing systems. Often for legitimate reasons – simplification for computing speed, for example. Few studies, however, have taken into account the localization of faults across whole systems. One of the more extensive examples highlighted in this paper (Han, Zhang and Wen [16]) provides extensive analytical studies relevant to localization on a duel disk setup, utilizing Hilbert-Huang Transforms – however in this example comprehensive validation is lacking, thus limiting the potential applicability of the research.

This problem is not limited to modeling and simulation-based research. Many newly-developed data-driven techniques for diagnostics and prognostics claim good results by heavily instrumenting specific components of a test system. In many industrial cases, this is not possible, practical or cost-effective.

To give some examples: a keyphasor transducer can be particularly useful in diagnosing faults such as rotor bow. However, this equipment requires the ability to cut a keyway for measurements to be performed. Optical sensors have recently been applied to detect rotor unbalance; yet such a technology would be difficult to implement in a system with several rows of rotors (as in a gas turbine).

Whilst new diagnosis and prognosis techniques for faults in rotating machinery are being continuously researched, the lack of corresponding studies into localization can be considered one of the many challenges in promoting recent core research into live industrial applications.

### *3.4 Fault Differentiation*

One promising development in recent modeling and simulation of rotordynamic faults is that of fault differentiation. Several researchers have moved on from studies on individual faults in order to concentrate on combinations of faults. As stated, rotordynamic faults such as those listed in this paper are linked to each other. Such studies, therefore, concentrate on such topics as a misalignment causing an unbalance or a looseness causing a rub. Findings from reports such as these are important in understanding complex anomalies. In industrial applications, simply detecting and rectifying an unbalance does not provide a satisfactory solution if the root cause of the fault is a misalignment. This is a complex topic, as several faults can exhibit similar vibration characteristics, making traditional detection techniques inaccurate in some cases.

Making reference to some of the aforementioned studies, those such as Nahvi and Silani [24] and Inoue, Nagata and Ishida [26] indicate some initial studies including several faults. The results of such studies indicate a high success rate in differentiating the faults in the given conditions; however a number of limitations still exist. Studies such as these consider unbalance in the fault chains. This is typically ‘static’ or simple unbalance applied to a single shaft/rotor – in reality unbalance faults can be more complex than this. In addition, the simple systems used to study and differentiate faults are very different from the complexities of a full turbine. However, further work may enable such research to ‘scale-up’ to this stage with the aid of further validation and verification

### *3.5 Prognosis*

It can be seen from the examples of recent research described for common faults that prognostic techniques are a topic where much work is being performed. Some of this work would be very difficult or impossible to implement in an industrial situation, others provide promising results of use to future work in the area. Predicting the remaining useful life of components is critical in the development of condition-based monitoring strategies for industrial implementation.

It can be noted that prognostic studies for certain rotordynamic faults are considerably more advanced than for others. The most obvious examples of the faults detailed in this paper are bearing faults, shaft and blade cracks. These are also areas where physics-driven simulations have had an important impact. The ability to design any fault type (or combinations of faults) into such simulations (be it low-fidelity mathematical models or high-fidelity finite element analysis) has provided researchers with many different avenues to explore. Studies into the prognostics of other faults can be complicated by various factors. An unbalance, for example, has had relatively little research performed into prognosis. The fact that unbalance is often the cause of another underlying fault is one reason for the difficulty in researching prognosis

in detail for this fault. The results of unbalance are also very dependent on the severity of the fault and the system in which it occurs.

It is worth noting that even for the faults where prognosis research is more advanced (shaft cracks for example); true development of the fault is not always studied. Fan [18] for example, studies sets of discrete cracks in order to ‘prognose’ crack growth. In fact, this study is more akin to detecting fault severity with inferred effects on crack growth. In contrast, Li *et al* [23] considers the continual development of such cracks – however the authors do admit this work is in its infancy. Such points limit the ability for true prognosis to be achieved without extensive operational data.

It is also worth noting that combinations of faults have been simulated extensively for the purpose of diagnostics, however few studies exist combining faults for the purpose of prognostics. Such studies are, however, a logical progression from some of those already performed. It may be that such prognostic studies build upon some of the Condition Based Maintenance (CBM) for diagnostics. High-level studies such as Jaw [36] indicate how prognosis and diagnosis techniques can be combined into a CBM system. This study is designed for a military aero engine, indicating the desire for such systems to be implemented – although the architecture described has the capability of including various algorithms for fault prognosis, the amount of consideration for prognosis of fault combinations is unclear.

### *3.6 Modelling*

The large number of works reviewed for this paper which include modeling techniques in order to aid diagnosis and prognosis indicate the possibilities provided by modern computer power and software development. Broadly, the modeling studied in the aforementioned papers breaks down into two categories: mathematical modeling and finite element analysis (FEA). The mathematical models, such as Qiu and Chapman [22], often provide a theoretical basis upon which data driven or FEA studies can build and validate. Mathematical models, despite being a traditional approach to rotordynamic problems, therefore continue to be developed to tackle more advanced problems.

FEA techniques offer a constantly expanding area of simulation to explore. They are used for research as diverse as crack propagation to unbalance localization [37]. Modern codes such as NASTRAN and Ansys enable rotordynamics to be studied beyond the traditional stress and modal analysis. The ability to study the effects of rotation (e.g. through Campbell diagrams and transient analysis) continues to drive research and innovation in this area. The studies discussed in this paper indicate the power of FEA, with some highly accurate simulations having been performed. However, there is still a limitation of computer power – applying some of the FEA techniques to whole engine models would prove to be too computationally expensive to be viable. As a result, alternate methods such as model order reduction and system level modeling (and model-based reasoning for implementation) are still required in order to make some of the FEA studies viable in an industrial environment.

Nonlinearities continue to form an important part of many recent studies, with the complexity and detail of the specified faults being continually expanded. The depth of modeling has enabled in many cases accurate validation against experimental approaches. Despite this, complete understanding of the vibrational phenomena of rotating machinery is not currently possible, despite the drive towards this end.

### *3.7 Rotordynamics and IVHM*

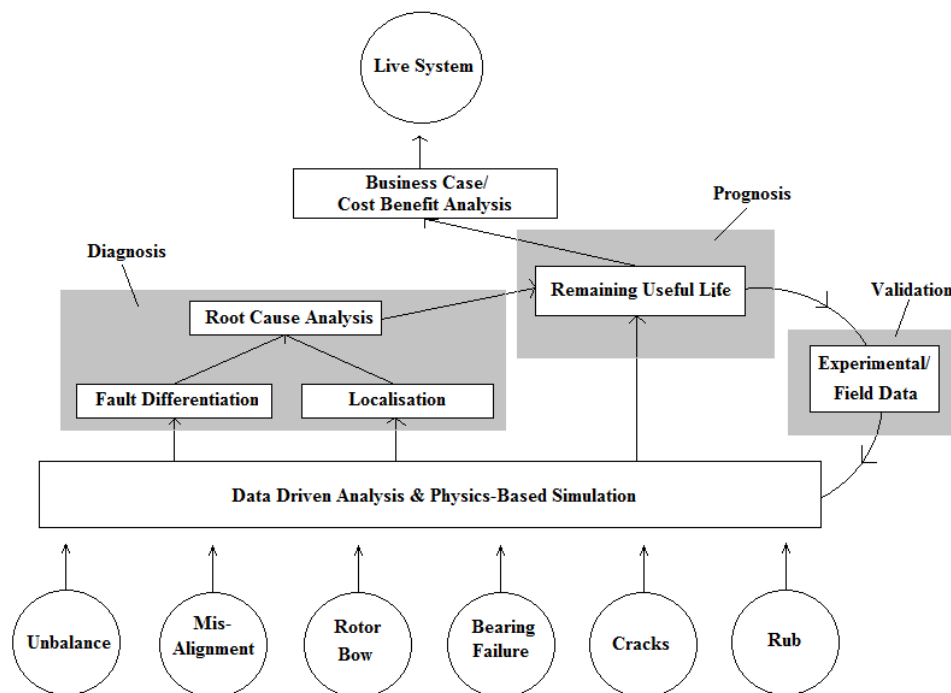
The bulk of current research into rotordynamics from the point of view of prognostic health management (PHM) can be roughly divided into two types: initial single-fault diagnosis/prognosis techniques and studies into the general requirements and limitations of current systems along with current and future trends. An example of the latter is Pusey [38]



who provides a good summary overview of current diagnosis and prognosis techniques with regard to condition-based maintenance.

As a result of this split, a clear gap exists between the core research being performed into rotordynamics from a condition-based maintenance perspective and the identified needs of industry. Taking a fledgling piece of research and applying it to a commercially-ready system (e.g. a gas turbine engine for an aircraft) is a long and complex task. It is nevertheless worth noting that technologies for automatically detecting an unbalance or misalignment in a gas turbine were developed over 10 years before the latest commercial aircraft were conceptualized, and yet these planes are still limited in this capacity. This highlights the need for work which links the fundamental research into individual fault diagnosis to ‘live systems’ in use in industry.

Physics-based simulation and modeling of rotordynamic parts is a well-researched field. Such modeling has been used as the basis of diagnosis and prognosis of faults by many researchers; several recent examples have been outlined in this paper. Occasional pieces of work have been performed into modeling multiple faults, such as Jain and Kundra [39] who use a system model for online identification of unbalance and cracks. Beyond this, however, very limited research exists. The demands of PHM techniques in industry are such that any system must not only be capable of detecting multiple faults, but must also be capable of detecting these faults across a range of different systems. Other considerations include the afore-mentioned ability to differentiate between multiple faults. Processing also needs to be taken into account, as the objective of these systems is to implement efficient condition monitoring and condition-based maintenance procedures. If processing data is a long, power-hungry process, then this aim cannot be achieved.



**Figure 7.1:** Physics-based simulation – from research to industry

Figure 7.1 details a potential framework required in order to push core research, such as that detailed in this report, towards industrial applications. Many studies now exist on individual rotordynamic faults across a wide range of conditions and applications. Some studies have taken this further, with advanced prognostic models and diagnosis of dual faults (primary

cause and secondary effect). Future research in the area of rotordynamics from a PHM perspective could potentially provide the bridge between these studies and live systems, by combining physics based simulations with data-driven techniques and validating against experimental data.

Although quantifying the success of the research studied is difficult, it is possible to define the key areas in which a technique must excel in order to be considered viable. The work by Wheeler [40] discusses in detail metrics for diagnostic and prognostic analysis, as does that by Vachtsevanos [41] and Saxena [42]. The conclusions drawn from these papers and applied in practice to research like that covered by this paper indicate that the following metrics are important when considering the potential of a given technique to diagnose faults: coverage, false positive rate and false negative rate. In the case of prognosis, probabilities and lead time to failure are other important considerations. This criteria enables research to be assessed in terms of its suitability for industrial applications. Unfortunately, information on these metrics is not made readily available by the authors of most papers.

In terms of evaluating the effectiveness of the research discussed in this paper, there are difficulties in recommending a specific technique over others for general application. Most papers reviewed for this document (not just those referenced and discussed in detail) take a technique (new or evolved), validate for a given, specific system and report success of the research. Despite this, some conclusions can be drawn from assessing common techniques applied across different studies and different faults. Although it is not possible to define the most common methods for diagnosing and prognosing faults in terms of numbers (as it was not possible to cover all recent rotordynamics research for this paper), as perceived by the authors the following techniques have featured prominently in the reviewed research:

- **Sensors:** Accelerometers
- **Theoretical Studies:** Mathematical Modeling
- **Physics-Based Simulation:** FEA
- **Data-Driven:** Joint Time/Frequency Domain Analysis
- **Implementation:** Neural Networking

These techniques appear to be among the most promising currently under development, as they tend to feature numerous times amongst some of the work with wider scope, across fault types and with the most comprehensive validation. There are of course many subsections to these techniques; however it shows one general direction of research and the clear possibilities posed in these areas.

Future developments in the field of IVHM for rotating machinery may incorporate these techniques alongside extensive use of nonlinear modeling and multiple fault interactions. The field of design for IVHM has only recently emerged, however the potential exists for specific nonlinearities to be designed into a system in order to enable accurate diagnosis and prognosis of faults. The development of current algorithms to include diagnosis, localization and prognosis of a range of faults will provide a significant advancement for future generations of IVHM systems. This combined with cost-effective sensor suites indicates the potential for evolutions of some of the research detailed here to form part of next generation IVHM suites for rotating machinery.

## 4. Conclusion

This paper has reviewed some of the latest research around a number of rotordynamic faults –

namely unbalance, misalignment, rub and looseness, fluid-induced instability, bearing faults, shaft cracks, blade cracks and rotor bow. Each fault was reviewed from the perspective of sensors, diagnosis, prognosis, localization and modeling.

Key examples of recent work into the eight described faults have been detailed through works by a number of eminent authors. Additional work has been summarized and formatted for easy reference. Some current trends amongst the recent body of work include developments in the vast area of modeling nonlinearities, combinations of high and low fidelity modeling and synergy between data driven and physics based simulation approaches.

Despite the large volume of promising research reviewed, further development in a number of areas is required in order to produce effective next generation IVHM systems. As such, future developments may include fusion of and/or development of current algorithms to encompass all eight faults detailed, consideration of prognosis, diagnosis and localization achieved using a reduced, cost effective sensor suite.

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## **Appendix B**

### **Physics-Based Simulation for Health Management of Rotating Machinery**

#### **Reference:**

Walker, R., Perinpanayagam, S. and Jennions, I.K. (2011), “Physics-Based Simulation for Health Management of Rotating Machinery”, *The Eighth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies – CM/MFPT*, BINDT, Cardiff, 20-22 June 2011, vol 1.

# **Physics-Based Simulation for Health Management of Rotating Machinery**

Ryan Walker, Suresh Perinpanayagam and Ian Jennions  
Cranfield University IVHM Centre  
Cranfield, Bedfordshire, MK43 0AL, UK  
+44 (0) 1234 750111  
r.b.walker@cranfield.ac.uk

## **Abstract**

Data-driven techniques for diagnosing faults in rotating machinery have a long history. Such approaches undoubtedly have their strengths and much research is still being performed in this area - recently into gearbox and bearing faults in particular. However, with the increasing power and sophistication of simulation tools, new methods for diagnosis, localization and prognosis of faults are rapidly being researched. This paper outlines current developments in modeling and simulation for rotating machinery health management and discusses the potential for such technologies to move from the realm of research into live systems. Comparisons and synergies with traditional data driven methods are made and it is concluded that simulation-driven techniques have much potential for next generation PHM systems.

## **1. Introduction**

The diagnosis of faults in rotating machinery is an ongoing topic of research. Data-driven techniques have historically been at the forefront of this research, and continue to play a key role in the diagnosis and prognosis of a wide range of rotordynamic faults. Although the need for such data-driven methods is clear, recent developments in physics-based simulation have enabled different approaches to rotordynamic problems to be formulated.

An example of an obvious advantage of physics-based simulation can be found in the diagnosis and prognosis of crack growth, where finite element analysis (FEA) techniques have already saved industry large sums of money. Simulation-based diagnostics and prognostics are, however, not limited to areas such as this. The aim of this paper is, therefore, to discuss current developments in the field of physics-based simulation for diagnosis, prognosis and localization of rotordynamic faults and to discuss the potential for future implementation of such research.

The area of rotordynamic faults is a diverse one, where many types of fault can occur in many different kinds of machine. It is not pertinent to cover all potential rotordynamic faults, and instead a selection of the more common faults is described with regard to diagnosis using simulation techniques. The selected faults are unbalance, misalignment, rub and looseness, fluid-induced instability, bearing faults, shaft cracks, rotor cracks and rotor bow. These faults have been chosen due to being some of the more common problems which can occur in most types of rotating machinery, and the interlinking nature between them (for example, a misalignment may lead to an unbalance).



## **2. Rotordynamic Faults**

The following section details the afore-mentioned common rotordynamic faults with regard to recent physics-based simulation work and traditional data-driven methods. Research in this area of rotordynamics is particularly widespread, and so this paper outlines only a few recent areas of research.

### ***2.1 Unbalance***

This is one of the most common rotordynamic faults <sup>(1)</sup>; every rotating machine has an inherent degree of unbalance. Unbalance as a fault can, therefore, be defined as unbalance outside of a given tolerance level. A recent piece of research which demonstrates the ongoing development of data-driven techniques is that by <sup>(2)</sup>, who tested a technique for measuring operating deflection shapes in order to detect unbalance cases. These studies were conducted on a machine fault simulator – such simulators have the advantage of recreating faulty conditions quickly and easily, enabling a new dimension to data-driven diagnostic techniques. It is, however, worth mentioning that data for these experiments were collected using 14 accelerometers, which are easy to apply to such a simulator, but it may be much more difficult to configure this many sensors on a complex system.

Regarding physics-based simulation of unbalance as a fault, the work by <sup>(3)</sup> involved creation of a virtual bearing-shaft-rotor system, not dissimilar to the aforementioned machine fault simulator. Modeling and simulation was performed using ADAMS, demonstrating an efficient way to simulate and practice machine balancing without the need for alterations to real systems. It is of note that the authors of this paper stress the need for experimental data in validating their results, indicating the synergy required between data driven and simulation-based methods.

Localization and prognosis of unbalance pose a unique set of challenges, and as a result research is still somewhat limited in these areas. One recent work which claims to localize unbalance accurately is <sup>(4)</sup>, the authors of which use trending data and reasoning systems to locate localized unbalance and shaft bow across a system. Remaining useful life of unbalance is difficult to predict due to complicating factors. An unbalance may, for example, be a result of a misalignment or bearing fault – which could be considered a root cause. A misalignment may lead to unbalance which induces a rotor-stator rub. Such combinations of faults and underlying causes for unbalance lead to the need for remaining useful life predictions to be made based upon the exact nature of a specific fault.

### ***2.2 Misalignment***

This is another common fault which can potentially inflict considerable damage in rotating machines. As with unbalance, misalignment in a whole system can be complicated by secondary faults (e.g. a misalignment which causes a rub). Reference <sup>(5)</sup> is an interesting paper in this area due to the author considering unbalance, misalignment and cracks to produce a piece of software which will identify and differentiate these faults. It is claimed that the software is easily adaptable between different systems.

Reference <sup>(6)</sup> demonstrates interesting research into misalignment from the perspective of physics based simulation. The authors construct mathematical models of a simple rotor

system with a misaligned coupling and collect harmonic response data from this to assess the severity of different misalignment cases. Such models are useful throughout the life of rotating machines – from design to implementation, although again successful validation with experimentally obtained data is key.

As with unbalance, localization and prognosis of misalignment is a complex topic to research. Studies such as <sup>(6)</sup> can make accurate predictions for misalignment in a simple system with one coupling. However real systems (e.g. aircraft gas turbines) have many potential locations of misalignment. This is an area where few researchers have made an impact. Remaining useful life predictions for misalignment are complicated for the same reasons as with unbalance. Reference <sup>(7)</sup> is notable for construction of a prognostic health management system for flexible power transmission couplings. The authors use a combination of data driven and modeling methods, including finite element techniques and claim a 15% increase in accuracy over purely data-driven methods.

### ***2.3 Rub & Looseness***

Rub is always a secondary fault (i.e. a product of another fault such as looseness) and can lead to fatigue and wear. Rub and looseness can create complex vibration signals which are difficult to diagnose using traditional methods. Modeling and simulation of rub and looseness faults have been considered in several recent works. This includes <sup>(8)</sup>, which outlines a dynamic system model of a rotor-bearing-stator system embedded with a rubbing fault. This work is particularly interesting as it takes into account vibration signatures of a whole aero-engine, an important consideration if such research is to move into industrial applications. Reference <sup>(9)</sup> is a good example of how simulation techniques can complement data-driven methods. The authors of this work outline a finite element model of a dual-disk rotor-bearing system which incorporates a looseness-induced rub. The model is used to predict vibration signatures of such a rub, which can then be combined with trending data to produce a diagnostic system.

Localization of rub and looseness across whole systems is relatively lightly studied in literature. Many works (including those already cited) look at single or dual-rotor systems where localization of such faults is not an issue. In an industrial setting, complex systems may comprise many rotors in several compressor and turbine stages, significantly complicating diagnosis of such faults. Research into prognosis of rotor-stator rubs lies mostly within the domain of data-driven techniques. Modeling and simulation research can be used to support data-driven techniques for prognosis and condition-based monitoring. Reference <sup>(10)</sup> is an example of this; the authors use finite element modeling to construct a dual rotor model. Various types of rub-impact are then studied. Such studies can provide a wide range of information, which can then be combined with data obtained from live systems, potentially with seeded faults, in order to construct accurate remaining useful life predictions.

### ***2.4 Fluid-Induced Instability***

Fluid-induced instabilities (often referred to as whip and whirl) are potentially very serious faults which can result in wear, fatigue and extensive damage to machine components. Such instabilities can be found in interstage seals, fluid lubricated bearings and blade-tip clearances. Research into simulating and modeling fluid-induced instability has produced several works of interest to fault diagnosis of rotating machines in the last

few years. Reference <sup>(11)</sup> is a good example, where non-linear mathematical models are prepared for a rotor-bearing system. The models are then used to predict instability thresholds. Another good example is the extensive numerical analysis carried out by <sup>(12)</sup>, which results in a system for diagnosing faults including rub and fluid-induced instability, validated against experimental results.

Prognosing fluid-induced instability is a relatively lightly researched topic. Fluid instabilities can be covered as part of extensive research into remaining useful life of bearings. The potential exists for modeling and simulation techniques such as those detailed above to become a part of prognosis for fluid induced instabilities due to the fact that it can be very difficult to seed such faults into live systems for testing and evaluation. As with other faults detailed in this report, many studies have been performed with the aim of describing fluid-induced instabilities based on the measurement or simulation of single (or occasionally dual) rotor setups. Physics-based simulation with the aim of localizing fluid instability faults across a whole system can be limited by the complexity of both the fault and the system, hence, the simplification to single rotor-stator bearing systems.

## ***2.5 Bearing Failure***

An area where data-driven techniques are still providing the basis of much research in the field of rotordynamics is that of bearing failure. The title ‘bearing failure’ can cover a wide range of potential issues which continue to be studied in detail. Faults can occur in all parts of engine bearings – the inner and outer case, the cage and the rolling elements. Data-driven techniques have enabled accurate bearing diagnostics and prognostics to be described for a range of rotordynamic systems.

Despite the prevalence of data-driven research in this area, research from a physics-based simulation perspective has also recently produced some interesting papers of relevance to condition monitoring and health management of rotating machinery. This includes <sup>(13)</sup> who detailed a selection of aero engine bearing faults and their consequent effects on a rotor. Reference <sup>(14)</sup> is a good example of high fidelity modeling for bearing faults. The authors comment on and suggest tradeoffs between computational time and accuracy – always an important factor in computational fault models.

As so much research has been performed (and is ongoing) into bearing faults across a wide variety of mechanical systems, both prognostics and localization of bearing faults have been researched in somewhat more detail than some of the other faults detailed here. Despite this, much work still needs to be performed in order to translate some of this core research into industrial applications. Research such as that detailed above has made significant advances into determining bearing failure as the root cause of a malfunction. Detecting which bearing is failing across a complex system has received somewhat less research. Bearing prognostics is another area with much ongoing research being performed – both in the simulation and data-driven domains. To give an example, <sup>(15)</sup> combined grade life and extensive mathematical modeling techniques in order to produce prognostic models for aero engine bearings. Reference <sup>(16)</sup> is an example of pure data-driven techniques, the authors of this work making comparisons between traditional fast Fourier transform (FFT) analysis and enveloping techniques, again for use in aero engine bearing prognostics.

## **2.6 Shaft Cracks**

Another potentially serious fault in rotating machinery is shaft cracks, and so early detection of any such fault is highly important. Methods of crack formation and propagation can be diverse, and range from high and low-cycle fatigue to stress corrosion. Simulation and modeling of shaft cracks can have significant advantages over data-driven methods. Perhaps the most obvious advantage is the relative simplicity of inserting a fault into, for example, a finite element model as opposed to seeding a fault in a working industrial machine. As such, research into shaft cracks has been progressing steadily with the corresponding increases in computing power.

A clear synergy between data-driven and physics-based simulation research can be implied by a number of recent works of research. An example of recent advances from a data collection perspective is <sup>(17)</sup>, which details statistical models based on historical data for condition monitoring purposes. From a modeling perspective, <sup>(18)</sup> used finite element analysis to assess shifting natural frequencies, which are then combined with pattern recognition techniques.

The nature of shaft cracks has resulted in a wide variety of research being performed into both localization and prognostics of these faults (indeed, the two topics can be considered related). Recent examples of work in this area include <sup>(19)</sup>, which details crack localization using forced response modeling. Reference <sup>(20)</sup> describes finite element modeling of crack propagation, with validation against experimental results provided to demonstrate the validity of such modeling techniques.

## **2.7 Rotor Cracks**

Rotor cracks, if allowed to develop, can result in serious consequences. Cracks can form due to high centrifugal stresses across operational cycles (in the case of an aircraft gas turbine, for example, start up and take off through landing and taxi). As excessive crack growth can lead to catastrophic rotor/blade failure, early detection and prognosis of such faults are essential <sup>(21)</sup>. As with shaft cracks, physics driven simulation of rotor cracks is an area of significant research. This varies from high-fidelity finite element models to low-fidelity system and mathematical models. The recent work demonstrated in <sup>(22)</sup> is a good example of recent mathematical modeling from a diagnosis perspective. Reference <sup>(20)</sup> demonstrated high fidelity modeling, the authors used FEA to model crack growth, making comparisons and validating against an experimental rig. This work is particularly interesting as it outlines the advantages and drawbacks with the latest state-of-the-art modeling techniques.

Localization and prognosis of rotor cracks have also benefitted from recent advances in simulation and modeling. Reference <sup>(23)</sup> contains details of work on a novel active magnetic bearing system for use in the early detection, localization and prognosis of rotor cracks. FEA has also been used extensively to support rotor crack prognostic tools; <sup>(24)</sup> is an extensive example of recent work.

## **2.7 Rotor Cracks**

Rotor bows can be a primary source of unwanted vibration in gas turbines. The main cause of a rotor bow (rotor bows do not include bows due to gravity) are thermal differences in a system caused by operating conditions. It is noted in <sup>(1)</sup> that this non-

symmetrical thermal distribution can cause excessive unbalance to the extent where a gas turbine will not start correctly. Such rotor bows are common on start up or shut down, and are often accounted for in operational procedures. However, if thermal ‘hot spots’ exceed a given tolerance level, they can cause permanent unbalances due to rotor deflections. Such rotor bows can lead to other faults, including rubbing and looseness which complicate isolation and localization.

Traditional data-driven techniques for detecting rotor bows involve combinations of slow roll and vibration data <sup>(26)</sup>. More recently, mathematical modeling techniques such as that detailed in <sup>(26)</sup> have been used in order to diagnose residual rotor bows, and differentiate these faults from other sources of unbalance.

The little work that exists on attempting to localize rotor bows across complex systems tends to be data-driven in nature; see <sup>(27)</sup> the authors of which used statistical symptoms based on known data as a method of diagnosing and prognosing a number of faults, including rotor bows and unbalance. Prognosing rotor bows is a complex subject. As rotor bows are often caused by temperature deflections, making predictions for remaining useful life and potential future problems lies not only in the realm of mechanical rotordynamics but also to some extent in thermodynamics. The recent work detailed in <sup>(28)</sup> is of note for detailing diagnosis and quantification of various rotordynamic faults and describing the advantages of mathematical modeling over traditional vibration-based approaches. Another two works which are of interest with regard to modeling of rotor bows include <sup>(29)</sup>, the authors of which modeled a rotor-bearing system with a permanent rotor bow, looking at the impact of secondary faults such as rub. Reference <sup>(30)</sup> describes the importance of model-based fault identification techniques and outlines recent research in the area.

### **3. Diagnosis**

It can be seen from the research outlined in the previous section that the diagnosis of faults in rotating machinery is a subject of ongoing research. This involves the improvement and development of traditional vibration monitoring techniques, development of new data-driven technologies and novel research into physics-based simulation and modeling. In many cases, these topics of research are dependent on one another for reasons of validation, verification and speed of analysis. In several cases it can be seen that multiple faults have been modeled for the purposes of identification and isolation. However no studies have yet been performed which deal with all of the aforementioned faults. All of these faults are intrinsically related to one another. Complex combinations of faults have begun to be analyzed with the emphasis on developing new diagnosis techniques. Physics-based modeling has proven to provide significant advances with regard to specific faults, notably shaft and rotor cracks, where techniques such as FEA enable much easier, faster and cheaper test data then seeding faults into live systems.

It can be noted, however, that both high and low-fidelity modeling techniques are being applied to cutting edge research for all of the listed rotordynamic faults (and others not detailed in this paper). In addition to the advantages in the speed of obtaining test results, physics-based simulation is providing another dimension to data-driven techniques. System models are being used as part of logic and reasoning suites in the identification and differentiation of various faults. High-fidelity models enable

simulations of fault combinations for which is it not possible, practical or is prohibitively expensive in live systems.

Nevertheless, results obtained from modeling studies still need to be validated against proven data-driven techniques before implementation in industrial applications is possible. It is also of note from the literature reviewed for this paper that almost all modeling for the diagnosis of faults involves extensive simplification, often reducing potentially complex systems down to one or two rotor/shaft/bearing models. Adapting the claimed results from such research to systems with many rotors/bearings/shafts is important in improving existing rotating machinery diagnostic techniques.

#### **4. Fault Localisation**

Fault localization in rotating machinery is an important topic of research for future condition-based monitoring systems. Knowing not only what type of fault has occurred, but also where in the system is an important consideration which can influence maintenance procedures in complex machinery. It is worth noting from the literature surveyed for this paper that many studies have focused on diagnosis and prognosis of single rotor/bearing systems. Often for legitimate reasons – simplification for computing speed, for example. Few studies, however, have taken into account the localization of faults across whole systems. This problem is not limited to modeling and simulation-based research. Many newly-developed data-driven techniques for diagnostics and prognostics claim good results by heavily instrumenting specific components of a test system. In many industrial cases this is not possible, practical or cost effective.

To give some examples: a keyphasor transducer can be particularly useful in diagnosing faults such as rotor bow. However, this equipment requires the ability to cut a keyway for measurements to be performed. Optical sensors have recently been applied to detect rotor unbalance; yet such a technology would be difficult to implement in a system with several rows of rotors (as in a gas turbine).

Whilst new diagnosis and prognosis techniques for faults in rotating machinery are being continuously researched, the lack of corresponding studies into localization can be considered one of the many challenges in promoting recent core research into live industrial applications.

#### **5. Fault Differentiation**

One promising development in recent modeling and simulation of rotordynamic faults is that of fault differentiation. Several researchers have moved on from studies on individual faults in order to concentrate on combinations of faults. As stated, rotordynamic faults such as those listed in this paper are linked to each other. Such studies, therefore, concentrate on such topics as a misalignment causing an unbalance or a looseness causing a rub. Findings from reports such as these are important in understanding complex anomalies. In industrial applications, simply detecting and rectifying an unbalance does not provide a satisfactory solution if the root cause of the fault is a misalignment. This is a complex topic, as several faults can exhibit similar vibration characteristics, making traditional detection techniques inaccurate in some cases.

## 6. Prognosis

It can be seen from the examples of recent research described for common faults that prognostic techniques are a topic where much work is being performed. Whilst some of this work would be very difficult or impossible to implement in an industrial situation, others provide promising results of use to future work in the area. Predicting the remaining useful life of components is critical in the development of condition-based monitoring strategies for industrial implementation.

It can be noted that prognostic studies for certain rotordynamic faults are considerably more advanced than for others. The most obvious examples of the faults detailed in this paper are bearing faults, shaft and rotor cracks. These are also areas where physics-driven simulations have had an important impact. The ability to design any fault type (or combinations of faults) into such simulations (be it low-fidelity mathematical models or high-fidelity finite element analysis) has provided researchers with many different avenues to explore. Studies into the prognostics of other faults can be complicated by various factors. An unbalance, for example, has had relatively little research performed into prognosis. The fact that unbalance is often the cause of another underlying fault is one reason for the difficulty in researching prognosis in detail for this fault. The results of unbalance are also very dependent on the severity of the fault and the system in which it occurs.

Finally, it is worth noting that whilst combinations of faults have been simulated extensively for the purpose of diagnostics, few studies exist combining faults for the purpose of prognostics. Such studies are, however, a logical progression from some of those already performed.

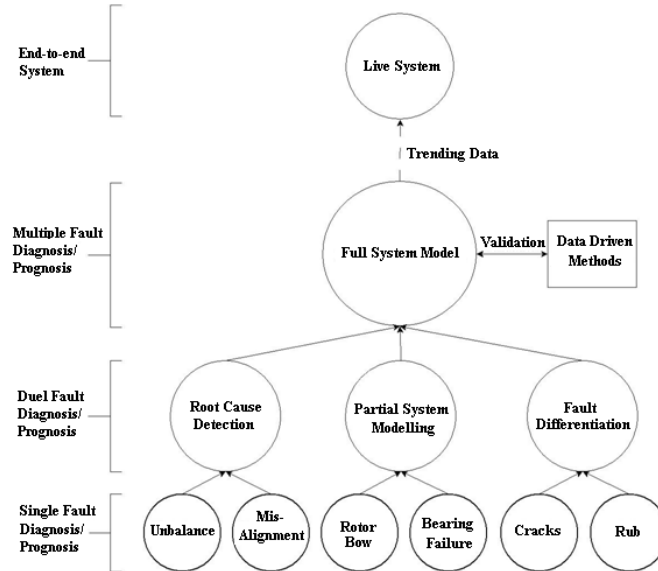
## 6. Rotordynamics and PHM

The bulk of current research into rotordynamics from the point of view of prognostic health management (PHM) can be roughly divided into two types: initial single-fault diagnosis/prognosis techniques and studies into the general requirements and limitations of current systems along with current and future trends. An example of the latter is <sup>(31)</sup> who provides a good summary overview of current diagnosis and prognosis techniques with regard to condition-based maintenance.

As a result of this split, a clear gap exists between the core research being performed into rotordynamics from a condition-based maintenance perspective and the identified needs of industry. Taking a fledgling piece of research and applying it to a commercially-ready system (e.g. a gas turbine engine for an aircraft) is a long and complex task. It is nevertheless worth noting that technologies for automatically detecting an unbalance or misalignment in a gas turbine were developed over 10 years before the latest commercial aircraft were conceptualized, and yet these planes are still limited in this capacity. This highlights the need for work which links the fundamental research into individual fault diagnosis to ‘live systems’ in use in industry.

Physics-based simulation and modeling of rotordynamic parts is a well-researched field. Such modeling has been used as the basis of diagnosis and prognosis of faults by many researchers; several recent examples have been outlined in this paper. Occasional pieces of work have been performed into modeling multiple faults, such as <sup>(32)</sup> who use a system model for online identification of unbalance and cracks. Beyond this, however, very limited research exists. The demands of PHM systems in industry are such that any

system must not only be capable of detecting multiple faults, but must also be capable of detecting these faults across a range of different systems. Other considerations include the afore-mentioned ability to differentiate between multiple faults. Processing also needs to be taken into account, as the objective of such systems is to implement efficient condition monitoring and condition-based maintenance procedures. If processing data is a long, power-hungry process then this aim cannot be achieved.



**Figure 1. Physics based simulation – from research to industry**

Figure 1 details a potential framework required in order to push core research, such as that detailed in this report, towards industrial applications. Many studies now exist on individual rotordynamic faults across a wide range of conditions and applications. Some studies have taken this further, with advanced prognostic models and diagnosis of dual faults (primary cause and secondary effect). Future research in the area of rotordynamics from a PHM perspective could potentially provide the bridge between these studies and live systems, by validating and combining with data-driven techniques.

## 6. Conclusion

It is clear that recent developments in physics-based simulation for rotating machinery health management have enabled another step to be made towards implementing PHM systems in many industrial applications.

Such modeling and simulation techniques have provided a new dimension in diagnosing, localizing and prognosing rotordynamic faults, in ways which data driven methods have not been able to.

Despite these advances, further research is required in order to implement these new technologies in industrial PHM systems. The need for research to be diversified from simple models with a single fault in order to cover whole, complex systems has been discussed along with the need for both simulation and data based research in achieving this aim.



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## **Appendix C**

### **Simulating Unbalance for Future IVHM Applications**

#### **Reference:**

Walker, R. Perinpanayagam, S., Jennions, I.K., 2012, "Simulating Unbalance for Future IVHM Applications", *The 2012 International Modal Analysis Conference*, SEM Inc., Jacksonville, February 2012, vol 4, pp 141-148

# Simulating Unbalance for Future IVHM Applications

Mr. Ryan Walker, Dr. Sureshkumar Perinpanayagam and Prof. Ian Jennions, IVHM Centre, Cranfield University, Conway House, Medway Court, University Way, Cranfield Technology Park, MK43 0FQ

## ABSTRACT

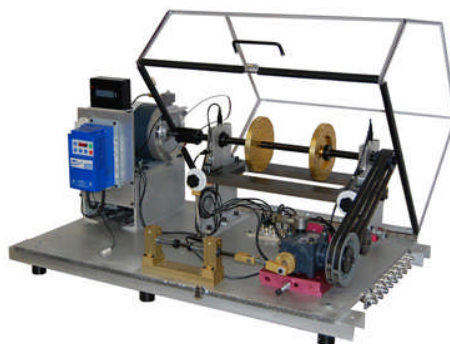
Unbalance is among the most common mechanical faults in rotating machinery, and is of particular interest to the aviation industry. A state of the art machine fault simulator has been used in order to recreate a range of unbalance faults which have been studied in detail from the perspective of fault localisation. High fidelity finite element models have been created in NASTRAN NX and experimentally validated against results for the machine fault simulator. The applicability of such simulations is discussed from an IVHM perspective, along with the potential for such research to influence the development of future engine health management with respect to improved safety and maintenance

## Introduction

As the aviation industry continues to work towards implementing complete IVHM (Integrated Vehicle Health Management) systems, the need for accurate fault diagnosis and localisation techniques for industrial applications is becoming increasingly urgent. One of the key areas of interest is rotating machinery, specifically gas turbines. Rotordynamics is a subject which has been studied in detail for many years; however techniques for the diagnosis and, particularly, localisation of faults have yet to be widely implemented in the aviation industry.

Gas turbines can suffer from a wide range of rotordynamic faults, from bearing failures to fluid induced instability. One of the most prevalent (and potentially serious) faults is unbalance [1]. Whilst unbalance faults in rotating machinery have been extensively studied from the perspective of diagnosis ([2-3] being two of many recent examples), techniques for the localisation of this fault are little studied [4].

The object of this paper is to describe studies into localisation of a range of unbalance faults from a simulation perspective. As 'seeding' unbalance faults into gas turbines is difficult and costly a state of the art machine fault simulator (MFS) has been used as the basis of the studies and for model validation. The machine fault simulator (see figure 1) enables unbalance weights to be added and removed quickly and easily, and a number of other faults can also be simulated for study. Simulation of the MFS has been performed using NASTRAN NX finite element software. This paper takes reference from and builds upon the work by [5], who used a similar setup to study damaged shafts from a simulation perspective.



1 Spectraquest Machine Fault Simulator

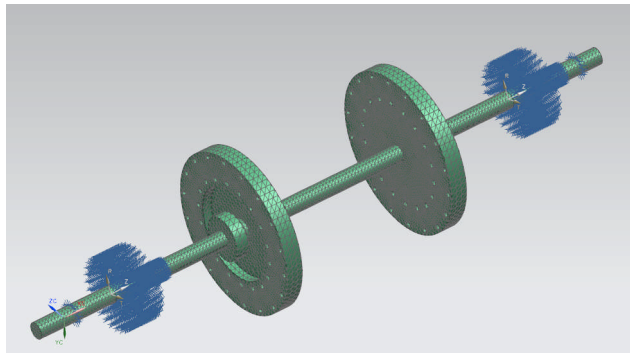
NASTRAN finite element models have been constructed and validated against the MFS, this takes the form of extensive hammer testing to identify modes of both the rotating parts and the support structure. In addition to this the complex eigenvalue solution for comparison against the rotating system with and without unbalance faults at various speeds has been considered. Based upon these experimental results, the FEA models were updated, validated and then expanded in order to

study fault localisation methods not possible/practical to do experimentally – even on the MFS, thus taking full advantage of the benefits of simulation.

The initial studies of this ongoing project which are outlined in this paper are concentrated on mode shapes and modal frequencies, with the aim of fully understanding the system and the effects of rotor unbalance for the purposes of localisation. Based upon the results collated here, a discussion is included that is aimed at outlining future work into fault localisation, including design optimisation for future IVHM systems and considerations required for implementing fault diagnosis and localisation techniques into industrial IVHM applications.

### High-Fidelity Model Validation

In order to correctly validate finite element models for further simulation, a high degree of accuracy is required (at least initially), involving a combination of accurate material properties, precise dimensions and appropriate constraints. Of particular relevance to rotating machinery are the bearing points, and providing stiffness and damping factors which sufficiently represent the system in question. In order to achieve the desired aims, the modelling procedures outlined in [5] provided a starting point, from which increasingly accurate models have been developed by incorporating accurate geometry and further developing bearing stiffness and damping factors for validation by hammer testing. Figure 2 displays the finite element model in meshed and constrained format. Initial models began with a simple constraint system on the bearing points (five fixed degrees of freedom, one free rotational). This was then developed by the addition of one-dimensional stiffness/damping elements linking the shaft with the fixed constraints.

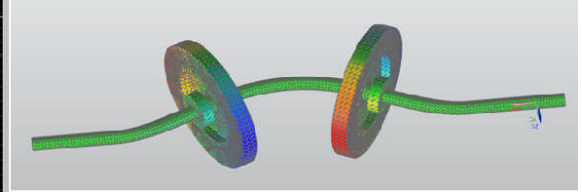


2 High-Fidelity FEA Model

Hammer testing was performed in free-free and fixed-fixed configurations, with the first ten modes identified from the finite element model initially studied (resulting in a frequency range of 0-1000hz). Figure 3 demonstrates an example correlation between the experimental hammer test and the FEA (finite element analysis) results. Table 1 displays the first ten modes from fixed-fixed simulation configuration against the hammer test results. Not all predicted modes from the FEA analysis are visible in the hammer test, however those that could be correlated were catalogued and used to tune the finite element model in order to produce the results displayed in Table 1. A similar study was produced using a free-free setup for the purposes of validating the initial rotor model before applying the bearing constraints. By altering accelerometer positions around the system it was determined that the detected mode at 110hz was the first bending mode (shown in NASTRAN simulation in figure 3), the third bending mode was detected to be at 353hz which displayed the clearest indication of any mode detected by hammer test.

After the rotor-shaft system was validated for normal operating conditions, a series of faults were induced into the model and a complex eigenvalue analysis performed in order to study the effects on the rotating system. Experimental results are detailed in a spectrogram (figure 4) for normal (left) and faulty (5.8g static unbalance, right) operating conditions. These experimental results display frequency shifts which can be correlated to those predicted from the complex eigenvalue simulation analysis, in this case the rotational speed was 25hz. Table 2 displays the results of the complex eigenvalue analysis frequency shifts from normal to faults conditions for a rotational speed of 25hz.

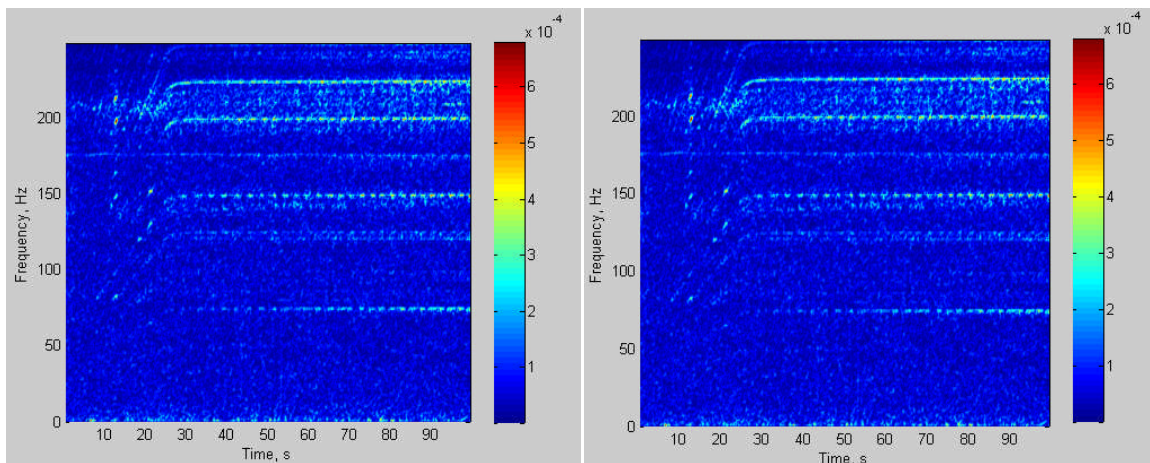
Repetitions of these experiments at different rotational speeds were used to validate the simulations against results from the MFS for the frequency range 0-1000hz, covering the first 10 modes. Building upon these results, a finite element model of the MFS structure was created in order to identify structural modes and provide a rounded view of the experimental information collected from the experimental results. The structural model can be viewed in figure 5.



**3** Hammer test experimental and simulation correlation

### 1 Hammer test experimental and simulation correlation

Mode Number	NASTRAN NX (Hz)	Fixed-Fixed Hammer Test (Hz)
1	112.4	110
2	157.9	Not detected
3	158.0	Not detected
4	196.2	192
5	360.1	353
6	360.1	353
7	581.8	580
8	581.9	580
9	635.3	640
10	635.4	640

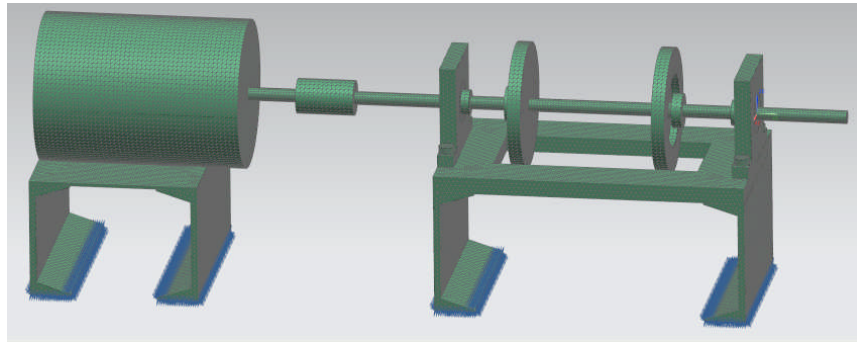


**4** MFS 25Hz Spectrograms without fault (left) and with fault (5.8g unbalance, right)

### 2 Modal frequency shifts from normal operating conditions for 5.8g

Mode:	1	2	3	4	5	6	7	8	9	10
Frequency Shift (Hz):	1.16	1.50	1.30	2.7	8.9	4.8	2.5	1.4	4.8	4.0





5 Full MFS finite element model

Due to the large number parts connected to the support structure (gearbox, electric motor, reciprocating ‘piston’ etc) identifying all of the structural modes would be a complex and unnecessary task. Despite this, identifying the key structural modes present in experimental studies was important so that they could be separated from the behaviour of the rotating system. With this in mind a number of finite element studies were performed using the aforementioned model, intended to interpret structural modes identified from hammer testing. In figure 6, two accelerometers were placed on the structure, one on the motor-side bearing housing (white) and one on the centre of the support plate (red). In this case the complex nature of the response can be seen, however from matching with the simulation results, structural bending modes were identified at 140hz and 560hz. The frequency range 0-1000hz was again studied for the purposes of this test, with repeat experiments carried out using accelerometers at different positions around the support structure.



6 MFS support structure hammer test, 0-1000hz

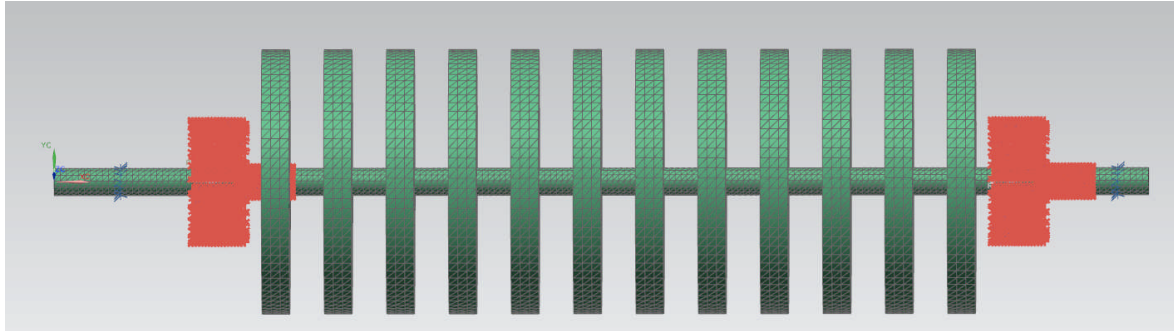
Using the data collected from experimental studies, the final calibration of the finite element models could be performed. This in turn led to the simulations assisting in identifying the phenomena which were observed from the experimental studies. The result indicated that the final set of finite element models could be considered to be validated to a suitable degree of accuracy, taking into account the desire to equate numbers between simulation and experiment along with the need to use simulations to produce future trending data.

### Fault Localisation

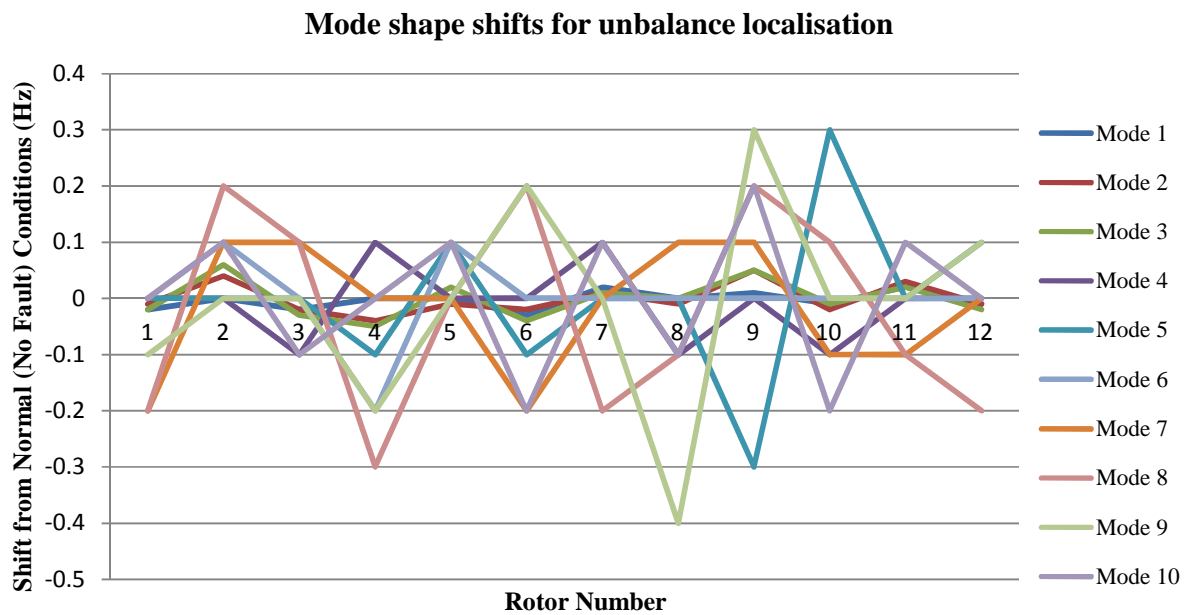
Using the set of validated finite element models, the next stage of simulation was to study mode shapes and modal frequencies for potential use in localising unbalance faults. In this regard, simulation presented several advantages over an experimental MFS. From an experimental perspective, the MFS contains two rotors – opening the possibility to localise a fault to one (or both) of these rotors. Using simulation, it is possible to extend this to a situation where 12 rotors are fitted. This is of interest as many rotating machines, gas turbines providing one example, contain many rotors in several ‘stages’.

The ability to localise a fault to one section of a machine could produce several enhancements with maintenance and safety – including the ability to speed up fault finding and part replacement.

In order to study this aspect, a model was created which maintained the shaft and bearing dimensions of the original model (and thus actual MFS), however applied 12 equally-spaced rotors along the length of the shaft. A simple 13.3g static unbalance was applied to each rotor in turn, monitoring the shifts in modal frequency depending on the position of the unbalance within the machine. The 12 rotor model can be seen displayed in figure 7, with the results displayed in figure 8.



7 '12 rotor' MFS model for unbalance localisation



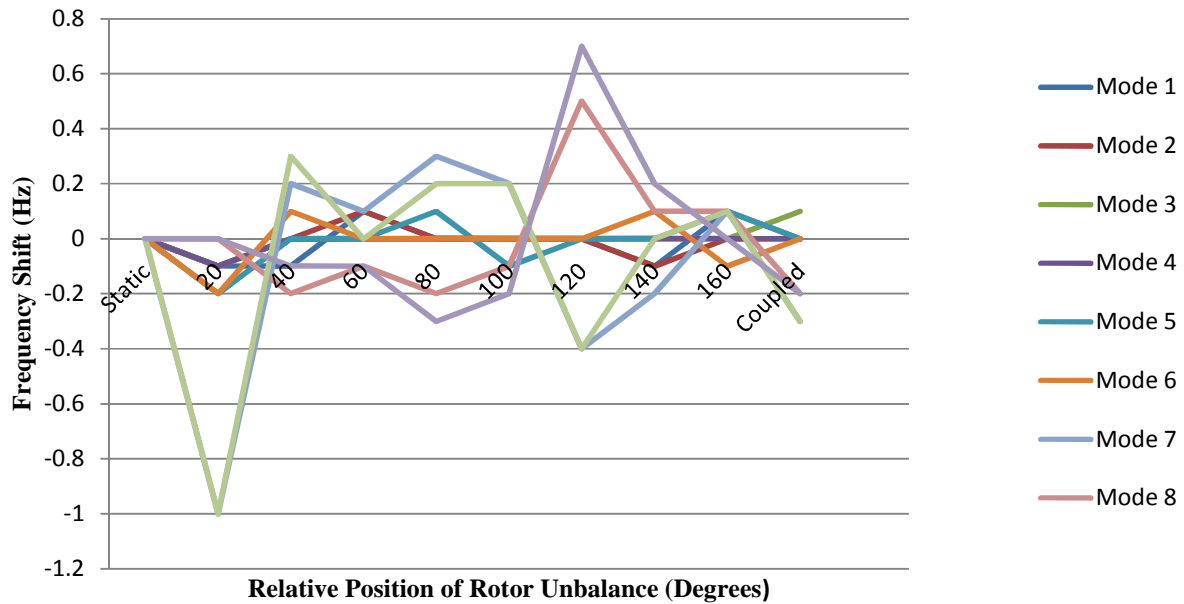
8 Modal frequency shifts for '12 rotor' model. Rotor '1' closest to motor end, rotor '2' farthest from motor end.

In figure 8, rotor 1 refers to the rotor positioned closest to the motor and rotor 12 refers to the rotor positioned farthest from the motor. A detailed, finely-meshed, simulation was used in order to reduce model error – however from repeat experiments it is estimated that a model error of  $\pm 0.1\text{hz}$  is incorporated in these results, and therefore only shifts in frequency greater than  $0.1\text{hz}$  can be considered valid. It is also worth noting that, although the rotors are equally spaced, due to the bearing points and motor position the model is not symmetrical. The results produced in figure 10 display clear defining features when the unbalance is applied to certain rotors, with less well defined features on others. It would not be possible to accurately localise an unbalance based solely on these results, however in combination with further studies these results could potentially prove to be very useful.

Unbalance faults can occur on one rotor in a variety of forms; these include static, dynamic and couple unbalance [6]. With this in mind, another form of fault localisation could be considered to be localising an unbalance within one rotor, or, more specifically, identifying the type of unbalance which has occurred. In order to study this further simulation studies were

performed. For this case, the original finite element model of the MFS was used, with a variety of unbalance faults applied to the motor-side rotor. Starting at 'top dead centre' a static (single) unbalance was applied. This unbalance was then incrementally separated in 20° segments until the unbalance was separated by 180° (coupled unbalance). The resulting model displayed the characteristics shown in figure 9. Repeat studies estimated that this model contained a variation (error) of approximately  $\pm 0.2\text{Hz}$ , and therefore only results outside of 0.2Hz variation can be considered a good indication of variance from the static unbalance case. It is also of note that due to a shaft-rotor coupling, each rotor, whilst balanced, is not symmetrical. Once again the results do not provide a conclusive method of localising unbalance; however in combination with additional studies this can potentially be achieved.

**Unbalance mode shifts - Static to Coupled**



**9 Modal frequency shifts from static unbalance to couple unbalance in 20° increments**

#### Other Unbalance Studies and Observations

In addition to the results detailed above, some additional studies performed provide information valuable to future works. Unbalance as a fault can occur as an individual item or as a function of another underlying problem – such as a shaft misalignment. It is therefore pertinent to investigate if unbalance faults can be identified as an individual fault or a function of another malfunction. Table 3 displays the differences from normal operating conditions between mode shifts of the first ten modes for unbalance and unbalance + misalignment cases. The unbalance applied was 5.8g applied to both rotors; the misalignment was a 1mm misalignment at the rotor-end bearing point. The results are based on the same conditions as detailed for table 2.

**3 Modal frequency shifts from normal operating conditions for 5.8g unbalance and 5.8g unbalance plus 1mm bearing point misalignment cases**

Mode:	1	2	3	4	5	6	7	8	9	10
Unbalance	1.16	1.50	1.30	2.7	8.9	4.8	2.5	1.4	4.8	4.0
Unbalance + Misalignment	-0.5	1.9	1.5	3.0	5.6	3.4	4.4	9.0	3.9	1.6

The results in Table 3 indicate a relatively large difference between the plain unbalance and the misalignment cases. However, as only one simple combination of misalignment and unbalance has been studied, this alone is not enough to state

that unbalance can be identified as an individual fault or as part of a misalignment. Further investigation would be required in this area to correctly understand fault differentiation.

Also of note is the effect of the size of the unbalance on detection ability. All unbalances simulated for this paper are based upon those available for application on a MFS. It should be noted that in rotating machinery terms these are relatively large unbalances. In gas turbines, a much smaller unbalance than has been studied here can be deemed unacceptable. As size of the unbalance (as a function of rotor mass) decreases the variation in modal frequencies also decreases, thus complicating the ability to localise such faults.

## **Discussion**

The experimental and simulation work outlined in this paper indicates the first steps towards the production of a strategy for fault localisation. The work concerns mostly model validation and lower-order modal investigations. Accurate, high fidelity models have been used as a basis for validation of simulation for the purposes of future study. A level of validation has been achieved which has been deemed acceptable in these circumstances, following general and popular model validation techniques (namely hammer testing). The next stage in the investigation of fault localisation involved experimental and simulation studies to determine the effect of a variety of unbalance faults on modal frequencies, with the intention to use this information for fault localisation. The studies concentrated on lower-order modes, in the case of the MFS the first ten, or roughly 0-1000Hz.

In this frequency range, it is possible to relate experimental results to mode shapes and defined modal frequencies. The results obtained from simulation indicate that the possibility exists in order to develop such localisation methods (or strategies) using techniques such as these. However, due to a number of factors including the relatively small frequency shifts involved the results do not represent a complete method for localising unbalance.

In order for this aim to be achieved, it is necessary to look at a broader frequency spectrum and alternate methods of assessing frequency-spectrum changes. By incorporating medium and high-frequency information with that which has been obtained during this study, the possibility to localise unbalance faults is greatly increased. In addition to this, some other studies performed in this paper indicate directions for future research. In order to provide suitable unbalance localisation techniques which are valid in industrial situations a number of factors need to be considered. These include considering a wide range of possible faults so that overlap does not occur, with the potential for false localisation readings to be produced. Other considerations for future studies include the applicability of FEA models to determine the information necessary for fault localisation. High-fidelity models generate large amounts of data and take a long time to solve. Repeating the procedures here, along with any additional required studies in order to develop localisation techniques for large structures such as a gas turbine could quickly get unwieldy. With this in mind, techniques such as model order reduction could prove valuable for effective simulation and data gathering of larger structures. Another important factor discussed was the ability to differentiate unbalance from other common faults such as misalignment; as such cases complicate fault localisation and render it less effective.

Finally, for future unbalance fault localisation techniques to prove usable, data acquisition methods and sensor positioning must be considered. In a simulation/lab based environment this does not prove as large an issue as with large, complex systems. Therefore any resulting localisation techniques need to be compatible in systems where sensors can not necessarily sit on or close to the desired section of machine, thus resulting in a key consideration for future.

## **Conclusion**

This study in the simulation of unbalance in rotating machinery for fault localisation has produced a number of results relevant for the development of future IVHM systems. High-fidelity model validation provided the basis for accurate simulation results, with simulations and experimental work centred on a state of the art machine fault simulator. Lower order modes and modal frequencies were used as the basis for unbalance localisation studies. Summarising the results in can be said that with further research into medium and high-order frequency spectra, combined with such considerations as sensor placement could result in a comprehensive strategy for fault localisation for future IVHM systems.

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## **Appendix D**

### **Unbalance Localisation using High-Fidelity Simulations**

#### **Reference:**

Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, “Unbalance Localisation using High-Fidelity Simulations”, *The Ninth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies – CM/MFPT*, BINDT, London, June 2012, vol.1 pp 454-469

# Unbalance Localisation using High-Fidelity Simulations

Ryan Walker, Suresh Perinpanayagam and Ian. K. Jennions  
Cranfield University IVHM Centre  
Cranfield, Bedfordshire, MK43 0AL, UK  
+44 (0) 1234 750111  
r.b.walker@cranfield.ac.uk

## Abstract

This paper introduces investigations into the localisation of unbalance faults in rotating machinery by means of high fidelity finite element simulations. Validated models have been constructed in NASTRAN based upon a machine fault simulator capable of replicating a wide range of rotordynamic faults. These models have been used in order to study frequency domain information, including the use of frequency response functions. The results are discussed with regards to potential implementation in next generation IVHM systems through model reduction techniques for system level modelling.

## 1. Introduction

Unbalance faults are among the most commonly occurring <sup>(1)</sup> faults in rotating machinery. Many years of research has lead to innovative methods of diagnosing such faults in both data driven and simulation domains. The recent work by <sup>(2)</sup> or <sup>(3)</sup> provide but two examples of recent work into this area.

Whilst many techniques exist for the detection of unbalance, a further aspect to this problem is the localisation of unbalance within a complex system. With industry continuing to move towards more efficient condition based maintenance techniques, the accurate localisation of faults is becoming a more pressing subject. Taking the airline industry as one example, the ability to transfer the knowledge that not only has a fault occurred but the precise nature of this fault and location within the engine would enable a faster turnaround time, decreased maintenance costs and more time in the air.

It is around these reasons that the research in this paper is being directed. Approaching the problem from an industry perspective, current in-field and on-board diagnosis and monitoring techniques are centred on the analysis of frequency domain data, often without using advanced processing techniques. The work contained herein has therefore been designed to aid information gathering for unbalance localisation in industrial applications which do not rely on unique or novel algorithms for fault detection.

Recent research into unbalance faults in rotating machinery has taken place in both simulation and data-driven forms. Whilst both approaches have clear advantages, the continual need for experimental validation and verification combined with the power of modern simulation packages results in the need for a synergy between both domains when considering such problems. With this in mind, the localisation studies in this paper are based upon a machine fault simulator (MFS) from Spectraquest. This enables a wide range of rotordynamic faults to be studied in a lab-based environment - including unbalance.



With the MFS providing the basis of the studies, NASTRAN finite element software has been used in order to generate high fidelity finite element analysis (FEA) models. This approach enables localisation studies to be performed using a higher number of rotors than can be fitted to the MFS, whilst providing a base for validation and verification. A similar approach was conducted by <sup>(4)</sup> who used ANSYS FEA models to study damaged shafts, using the MFS as a base for studies. This previous work provided assistance with regards to constraints and validation of the NASTRAN model developed for the purposes of this paper. Validation takes the form of the industry standard approach of impact testing, combined with some operational comparisons of the MFS against the NASTRAN models.

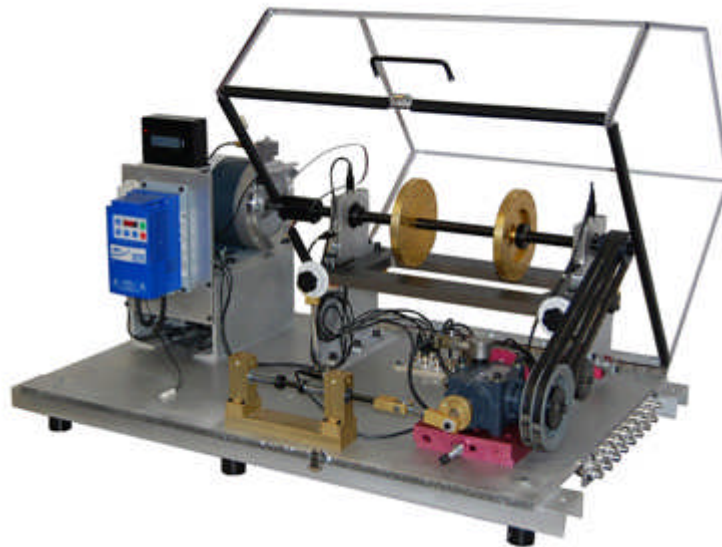
Using a successfully validated NASTRAN model, studies have been conducted of unbalance faults occurring throughout a 12 rotor system. The objective being to identify features which can be used to make observations as to the location of an unbalance fault within a system, and to provide this information in such a way that it can enhance the drive towards future integrated health management (IVHM) systems.

As a new generation of commercial aircraft begin to enter service, the drive towards condition based maintenance has taken another step. Looking forward, next generation IVHM systems need to be based around an adaptable formula which can be applied to a wide range of designs and models <sup>(5)</sup>. Hence the requirement for a broad approach to unbalance fault localisation.

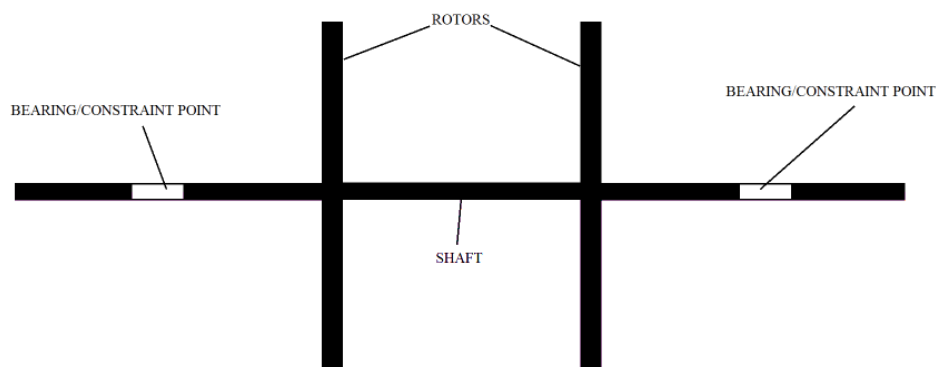
Due to the reasons detailed above, the research detailed in this paper has been split into three sections. The first deals with the construction of high fidelity finite element models of the MFS. This section also deals with model validation using impact testing alongside other validation methods. Following on from this, low order feature identification has been performed. This section covers the first ten modes of the MFS, detailing features identified which could be relevant to the localisation of unbalance faults. Finally, higher-order frequency domain features are studied in order to investigate the frequency range for which useful features can be identified, and in order to identify further features for use in fault localisation.

## **2. High-Fidelity Simulations**

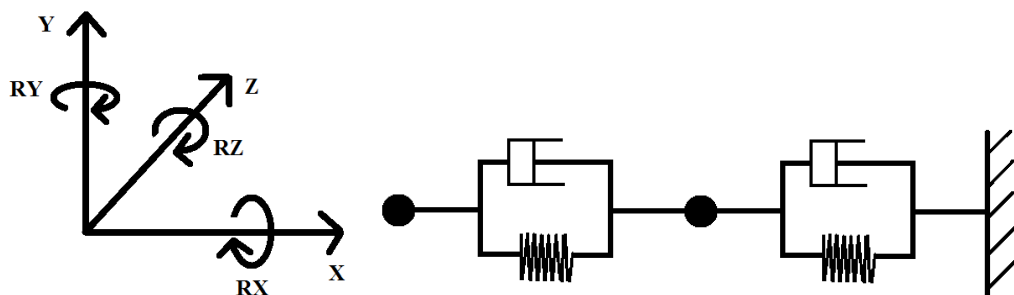
This paper builds upon the detailed work by <sup>(4)</sup>, which identifies a system of model parameters and constraints for a finite element simulation of the MFS. For the purposes of this paper, the same constraint system has been applied to a NASTRAN model (as opposed to ANSYS used by <sup>(4)</sup>). Additional developments have been made in an attempt to assist the validity and validation of the model. This includes the application of accurate geometry in the model, along with slight dimensional alterations in order to configure the model to the set up of the particular MFS to be used for validation. The MFS can be seen detailed in figure 1. Figure 2 details the model set developed for validation and localisation studies, whilst figure 3 demonstrates the coordinate system and constraint type used in the model validation.



**Figure 1. Spectraquest Machine Fault Simulator (MFS)**



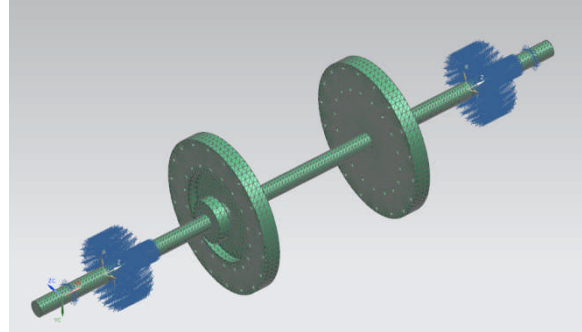
**Figure 2. Simulation setup sketch**



**Figure 3. Simulation constraint system <sup>(4)</sup>**

In order to correctly simulate the setup of the MFS in NASTRAN, the constraint system detailed in previous literature has been altered. In this case five degrees of freedom have been fixed (X, Y, RY, Z and RZ). In the manner shown in figure 3 (from <sup>(4)</sup>). The final degree of freedom (RX) is not a fixed constraint; however it has a stiffness/damping value assigned to mimic the role of the bearing points in the system. This constraint

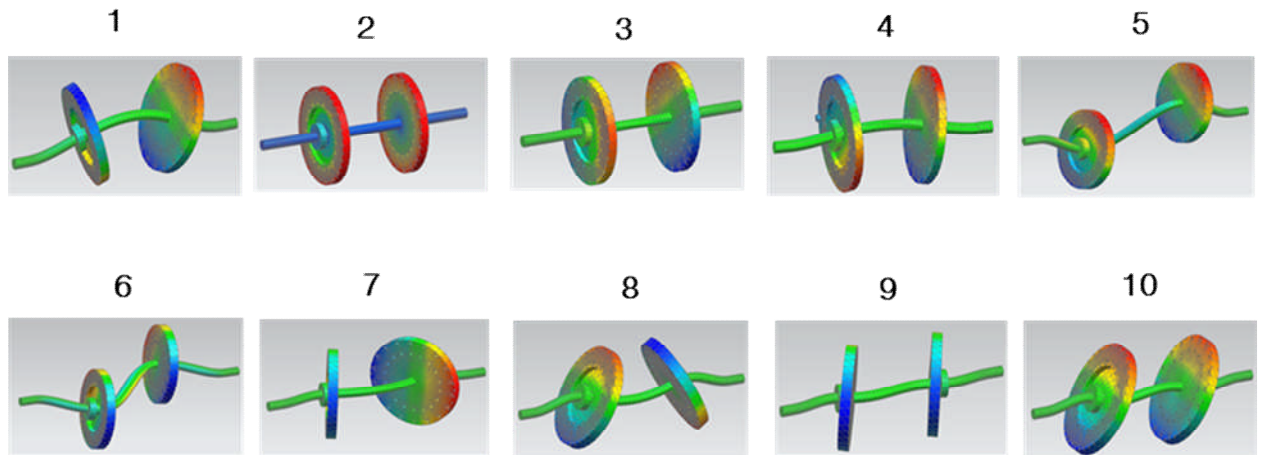
system was refined through a series of trial and error experimental validation studies. The geometrically accurate, meshed and constrained finite element model can be seen in figure 4.



**Figure 4. Constrained and meshed simulation**

Using this refined model of the MFS rotor and shaft system, the first 10 mode shapes were investigated for comparison against previous work in literature and for the purposes of experimental validation. The differences from the work performed by <sup>(4)</sup> can be attributed to different geometry along with the adjusted constraint system. Despite this, the results are largely coherent with those previously performed. In order to validate the model, hammer testing was performed for a frequency range covering the first 10 modes (in the case of the MFS, 0-1000hz). In this case, the identification of the modal frequencies was identified by clear peaks in the frequency spectrum, occurring at or near those frequencies predicted by the simulation. The mode shapes could then be affirmed by movement of the accelerometer along the length of the shaft to identify nodes and anti-nodes.

This validation procedure has been completed for both free-free and fixed-fixed setups (free standing system and fixed in the bearing points respectively). In figure 5, the first 10 mode shapes can see seen as defined by the NASTRAN simulation. An example hammer test is displayed in figure 6.



**Figure 5. First 10 NASTRAN MFS modes**



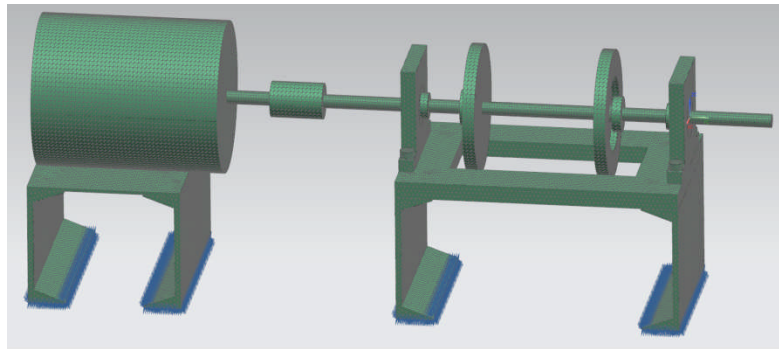
**Figure 6. Example hammer test**

In figure 6, a clear peak can be seen which indicates the first modal frequency at 110hz. In this case two accelerometers are attached in the nodal position in the centre of the shaft. This procedure was repeated from 0-1000hz, with the results summarised in figure 7. This table indicates the comparisons between the simulation results from the final NASTRAN model and the hammer testing. It can be seen that slight variation exists between the model and the hammer test. It is also relevant that the simulation predicted ‘double’ modes, which it is difficult to distinguish between on the hammer test. It is also often the case that not all modes predicted by simulation appear to be present during experimental tests. In this case, mode 2 and 3 were not distinguishable on the hammer test. Aside from this, the simulation results appear to be sufficiently valid in order to undertake further testing using the NASTRAN model.

<b>Mode Number</b>	<b>NASTRAN NX (Hz)</b>	<b>Fixed-Fixed Hammer Test (Hz)</b>
1	112.4	110
2	157.9	Not detected
3	158.0	Not detected
4	196.2	192
5	360.1	353
6	360.1	353
7	581.8	580
8	581.9	580
9	635.3	640
10	635.4	640

**Figure 7. Simulation and experimental comparison**

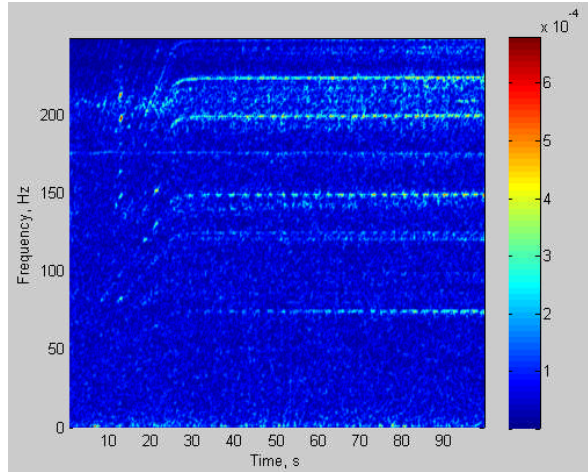
Further simulation for the purposes of evaluation included the study of structural modes, along with some operational validation of the results. In order to study the structural modes of the system, and identify some features present in the hammer test, a larger model of the MFS was constructed, detailing the full shaft and coupling, electric motor, bearings, mountings and base supports. This model can be viewed in figure 8. Whilst such a complex system with a wide variety of materials provided for a model which was not capable of simulating the whole range of modal frequencies present in the system; it is capable of indicating some of the more prominent structural modes.



**Figure 8. Full MFS structural simulation**

These structural modes indicated from the model in figure 8 were used in order to understand in more detail some of the phenomena detected when the MFS is in operation. The next stage of model validation involved the addition of an unbalance fault to the MFS and the corresponding NASTRAN models. This takes the form of a small weight screwed into the periphery of the rotor (for the validation experiments, a small unbalance was added in the same position to both rotors). It is planned that the MFS simulations will be expanded through the study of Campbell diagrams predicting the shaft in modal frequencies due to the rotational speed of the machine and the unbalance fault.

As a precursor to this, spectrograms were obtained from the MFS in operation at 25hz (an example plot is given in figure 9). Using the information obtained from the simulations, the operational modes at 25hz could be isolated from the structural modes and other phenomena. The shift in modal frequency due to the addition of the unbalance fault could then be compared for experimental results. All experimental results were obtained using NI Labview hardware and software, with accelerometers mounted on the bearing housing. The mass of the unbalance weight was 5.3g. The results from these comparisons can be seen in figure 10.



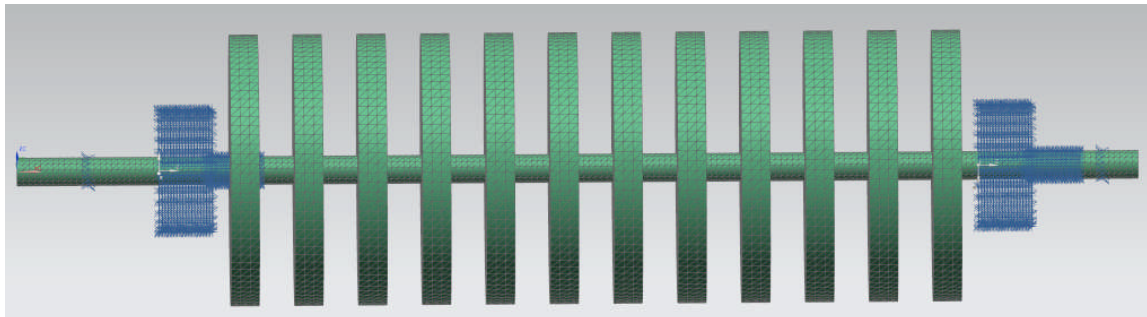
**Figure 9. MFS operational spectrogram**

<b>Mode:</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>
<b>Unbalance (Shift in modal Frequency)</b>	<b>1.16</b>	<b>1.50</b>	<b>1.30</b>	<b>2.7</b>	<b>8.9</b>	<b>4.8</b>	<b>2.5</b>	<b>1.4</b>	<b>4.8</b>	<b>4.0</b>
<b>Unbalance + Misalignment (Shift in modal Frequency)</b>	<b>-0.5</b>	<b>1.9</b>	<b>1.5</b>	<b>3.0</b>	<b>5.6</b>	<b>3.4</b>	<b>4.4</b>	<b>9.0</b>	<b>3.9</b>	<b>1.6</b>

**Figure 10. Shifts in modal frequency for faulty conditions**

### 3. Low-Order Feature Identification

With the two rotor MFS models judged to be validated to a sufficient degree, a new NASTRAN model was created for the study of unbalance localisation. Taking the same shaft dimensions and constraint system as the validated model, twelve equally-spaced rotors were placed on the simulation. The revised model was run with no faults induced, followed by a 5.3g (to mimic the standard unbalance that can be applied to the MFS) unbalance weight applied to each of the 12 rotors in turn. The 12 rotor meshed model can be seen in figure 10.



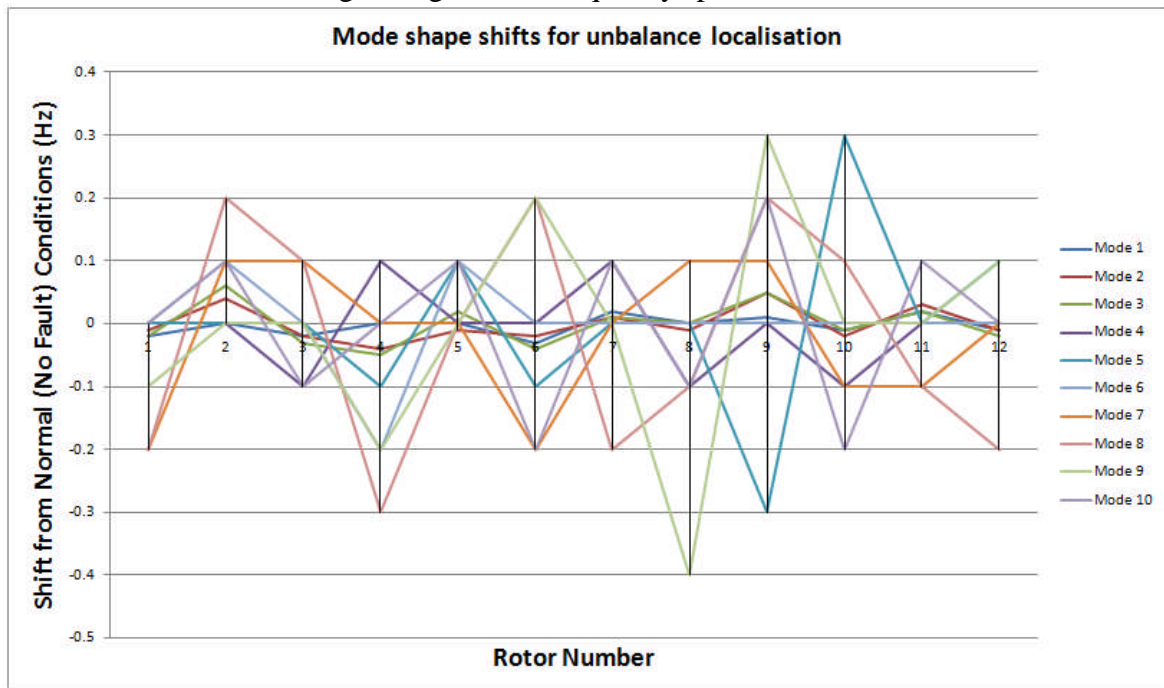
**Figure 10. 12 rotor 'localisation' model**

The results of the simulation can be seen in figure 11. This graph displays the shift in frequency, calculated in Hz, from normal (no fault) conditions. 'Rotor 1' indicates the rotor positioned closest to the motor, 'rotor 12' indicates the rotor farthest from the



motor. It is important to note that, whilst the rotors are balanced, they are not symmetrical due to the rotor to shaft coupling. Repeat runs, along with a conservative calculation of the inherent error in the model indicates that the results displayed are subject to  $\pm 1\text{hz}$ .

Incorporating this error into the results produces the summary in figure 12. In this case, highlighted cells indicate ‘useful’ information (or a confirmed shift in modal frequency above the model error level). The information displayed in the table indicates that in this case no useful information can be gathered from the first four mode shapes. The remaining modes give some information useful for the localisation of unbalance, however further studies were required in order to compliment this data. The data displayed in figure 12 is also inconclusive with regards to rotor numbers three, five and eleven. It is also of note that similar trends can be seen in rotor two and rotor seven. It is for these reasons that a larger range of the frequency spectrum needs to be looked at.



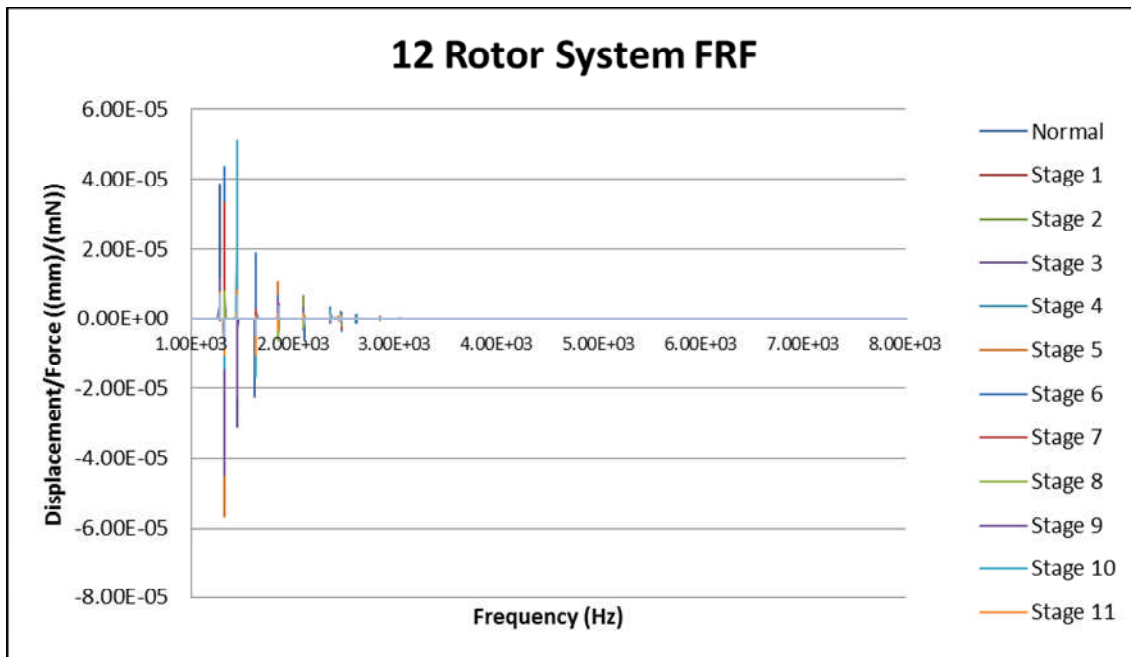
**Figure 11. Mode shape shifts for unbalance localisation**

	Rotor 1	Rotor 2	Rotor 3	Rotor 4	Rotor 5	Rotor 6	Rotor 7	Rotor 8	Rotor 9	Rotor 10	Rotor 11	Rotor 12
Mode 1	-	-	-	-	-	-	-		-	-	-	-
Mode 2	-	-	-	-	-	-	-		-	-	-	-
Mode 3	-	-	-	-	-	-	-		-	-	-	-
Mode 4	-	-	-0.1 Hz	+0.1 Hz	-	-	+0.1 Hz	-0.1 Hz	-	-0.1 Hz	-	-
Mode 5	-	-	-	-0.1 Hz	+0.1 Hz	-0.1 Hz	-		-0.3 Hz	+0.3 Hz	-	-
Mode 6	-	+0.1 Hz	-	-0.2 Hz	+0.1 Hz	-	-		-	-	-	-
Mode 7	-0.2 Hz	+0.1 Hz	+0.1 Hz	-	-	-0.2 Hz	-	+0.1 Hz	+0.1 Hz	-0.1 Hz	-0.1 Hz	-
Mode 8	-0.2 Hz	+0.2 Hz	+0.1 Hz	-0.3 Hz	-	+0.2 Hz	-0.2 Hz	-0.1 Hz	+0.2 Hz	+0.1 Hz	-0.1 Hz	-0.2 Hz
Mode 9	-0.1 Hz	-	-	-0.2 Hz	-	+0.2 Hz	-	-0.4 Hz	+0.3 Hz	-	-	+0.1 Hz
Mode 10	-	+0.1 Hz	-0.1 Hz	-	+0.1 Hz	-0.2 Hz	+0.1 Hz	-0.1 Hz	+0.2 Hz	-0.2 Hz	+0.1 Hz	-

**Figure 12**

#### 4. High-Order Feature Identification

With the need to look at further details of the frequency spectrum having been outlined, an alternative method of analysing the spectrum was required. At frequencies above 1000hz, assessing the mode shapes of the system can become difficult due to the complex motions encountered at higher modes. In addition, it is useful to provide an alternative (yet still relatively simple) method of picking features for localisation of the unbalance fault. Therefore, the frequency response function has been calculated across the 12 rotor model. A range of simulations was run in order to determine the optimum input and output positions for the FRF, eventually determining that a point on the centre of rotor 1 provided for the optimum input, with the same point on rotor 12 being used for the output. These points were chosen due to the clarity of output results provided. The range chosen for the frequency spectrum was 1000-8000hz. This continues from the lower-order frequency studies done, and continues up until the maximum point at which validation by hammer test is possible. This was deemed to be a wide enough frequency range for testing, inside which the useful frequency features could be identified. The results of the simulation can be seen in figure 13.



**Figure 13. Broad spectrum FRF**

In figure 13 the whole frequency spectrum can be seen from 1000 to 8000 hz. This overview indicates that the useful information contained in the system is concentrated between 1000hz and 3500hz. Further to this, as the differences between the different rotors are difficult to establish, focussing on each peak in the spectrum is required in order to extract any relevant information.

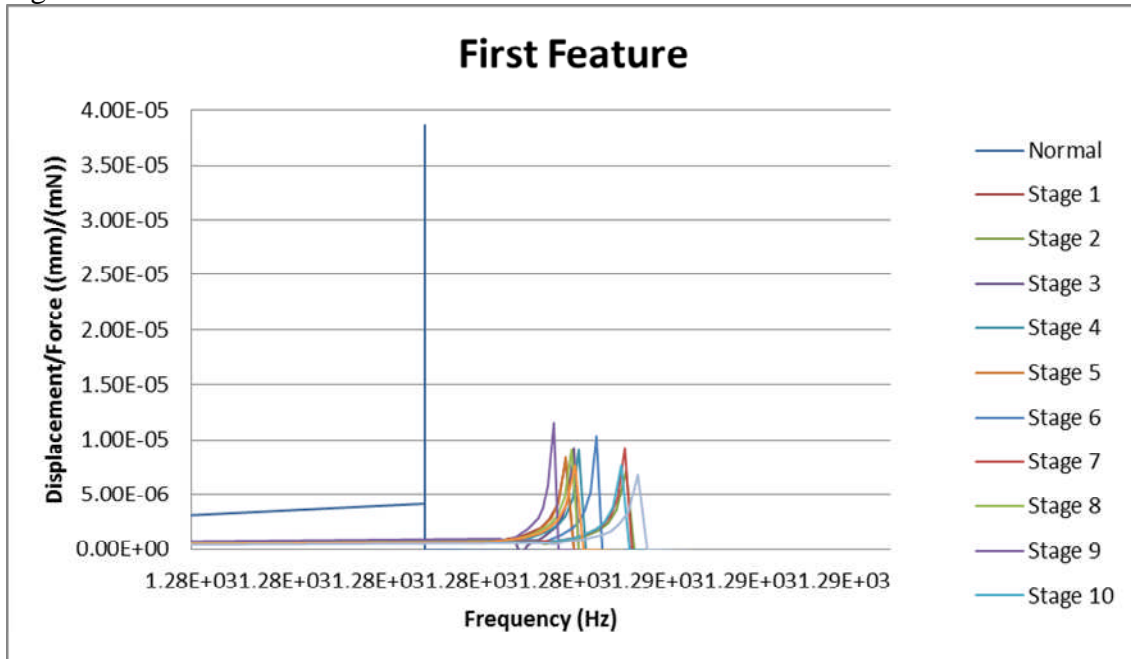
In figure 14, a close examination of the first peak on figure 13 can be seen. In this case the difference between normal and the faults conditions is clear. The difference between the peaks of the faulty conditions is more difficult to distinguish, however it can be noted that the peaks of the first six stages of the system are placed lower in the



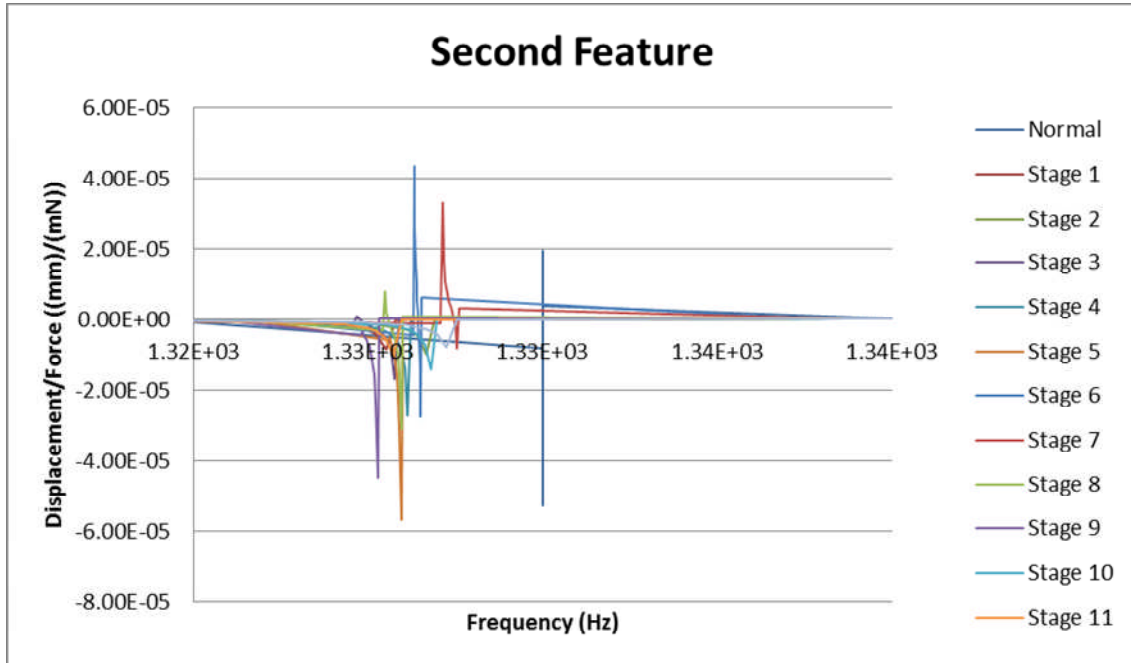
frequency spectrum than the last six stages of the system, the peaks of which reside further up the frequency spectrum.

In figure 15, the second peak can be seen in close up. This again demonstrates a large difference between faulty and normal operating conditions. From this it can be seen that the positive peaks indicate the two rotors in the centre of the shaft (6 and 7), all other peaks can be seen to be negative. The information that can be gathered from the next peak (figure 16) is not as clear, however it can be noted that rotor 4 and 10 experience a large positive displacement, whilst 3 and 9 are the only rotors to produce negative displacements in the FRF when an unbalance weight is applied to the rotors. The next two peaks in the spectrum do not exhibit any interesting behaviour, however around 2100hz the peak in figure 17 can be seen to indicate larger positive displacement peaks for the six rotors positioned closest to the motor than the six rotors positioned further away.

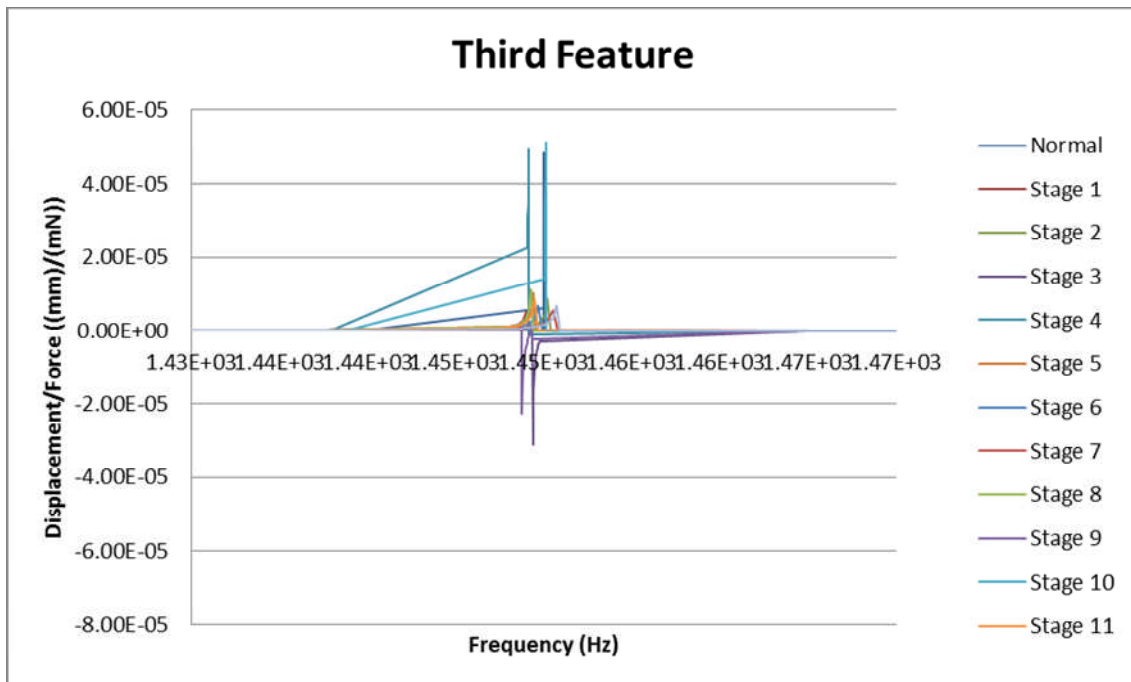
After this point in the simulation, the amplitude of the displacement peaks diminishes somewhat. However, an interesting sequence of features can be seen in figure 18. In this case, another difference can be viewed between those rotors at the motor end of the shaft (1-6) as opposed to those away from the motor end (8-12). In the case of rotor 7 (which is directly in the centre of the shaft due to the slightly offset dimensions), a unique pattern can be seen, with inverse direction peaks in the  $2.43 \times 10^{-3}$  to  $2.47 \times 10^{-3}$  region.



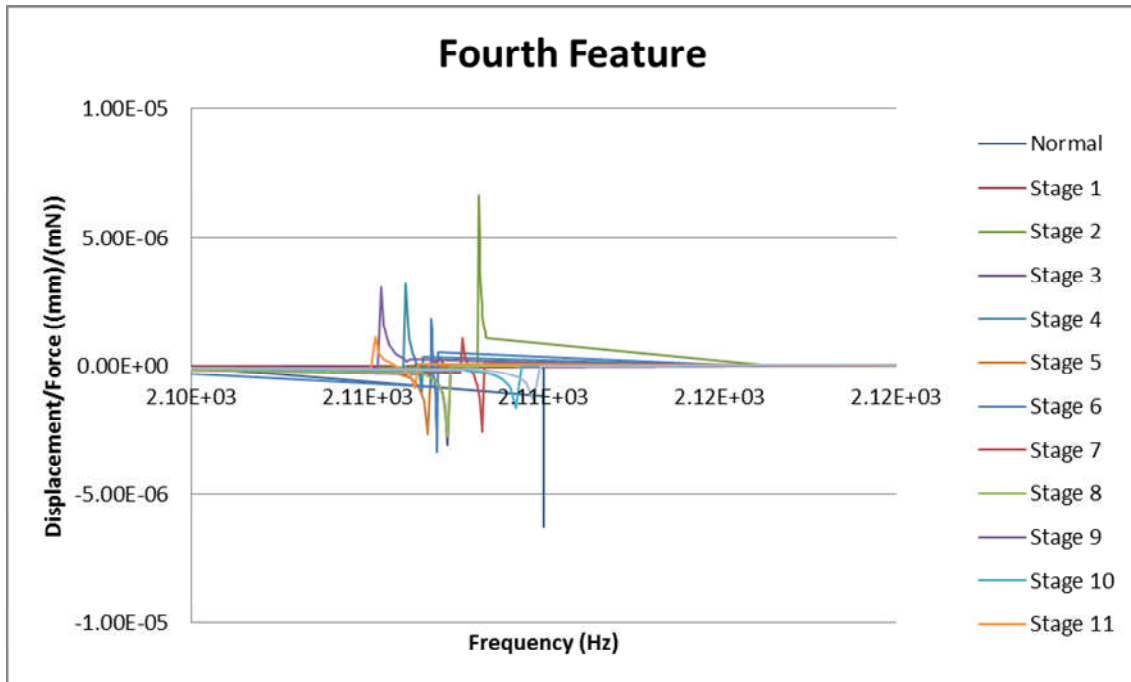
**Figure 14. First FRF peaks**



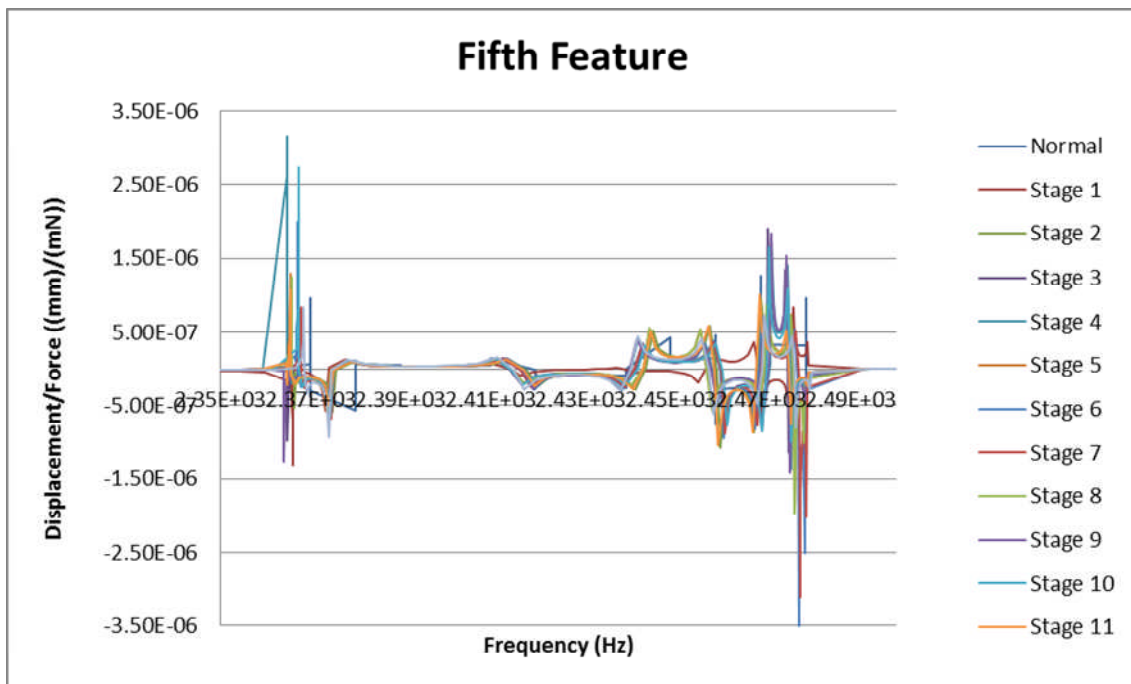
**Figure 15. Second FRF peaks**



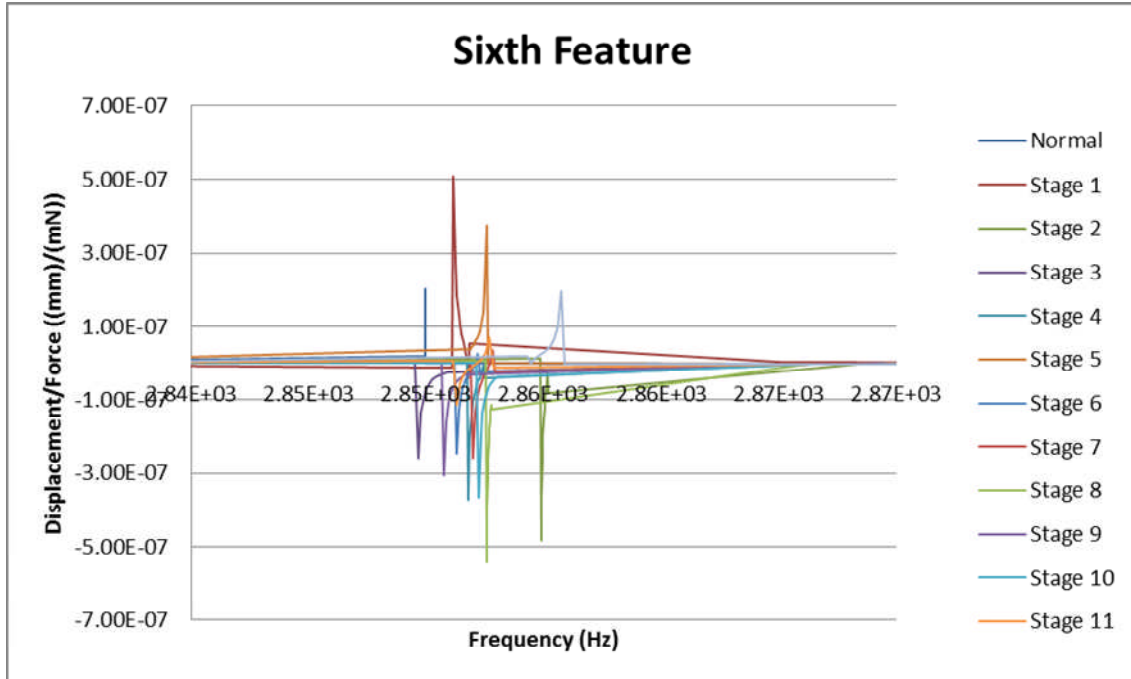
**Figure 16. Third FRF peaks**



**Figure 17. Fourth FRF peaks**



**Figure 18. Fifth FRF peaks**



**Figure 19. Sixth FRF peaks**

The final point of interest is displayed in figure 19, in this case it can be seen that the rotors at either end of the shaft experience positive displacement (1, 11 and 12), whilst the others (aside from normal, non fault condition) experience a negative displacement. After these points, the remaining frequency spectrum measured (~3000-8000hz) exhibits relatively few features, the amplitude and nature of which make the remaining results inconclusive. From the information gathered, analysis can be performed to provide recommendations for unbalance localisation.

## 5. Discussion

The results collected across a broad frequency range represent data which can be collected with relative ease from a wide range of rotating machines. As previously stated, this allows for localisation recommendations to be adapted to a number of different applications. Whilst a 12 rotor system was used for the purposes of studying the unbalance fault as it was placed in different positions down the length of the shaft, in order to summarise the results and provide suitable conclusions the localisation it is to be divided into three 'regions'. These regions are to be 'forward', 'middle' and 'rear', and refer to rotors 1-4, 5-8 and 9/12 respectively. This approach groups the results such that it is possible to predict with greater accuracy the portion of the machine in which the fault has occurred.

With the three regions defined, the results discussed in this paper can be surmised in tabular format, as detailed in figure 20.

	<b>Unbalance in Forward Region (Rotor 1-4)</b>	<b>Unbalance in Middle Region (Rotor 5-8)</b>	<b>Unbalance in Rear Region (Rotor 9-12)</b>
<b>Lower Frequency Features (0-1000hz)</b>	Negative shift in 7 <sup>th</sup> and 8 <sup>th</sup> modal frequencies. Positive shift in 8 <sup>th</sup> modal frequency only. Negative shift in 6 <sup>th</sup> , 8 <sup>th</sup> and 9 <sup>th</sup> Modal Frequencies.	Frequency shifts in modes 7-10. Distinct frequency shift in 9 <sup>th</sup> mode only.	Distinct frequency shifts in 5 <sup>th</sup> , 8 <sup>th</sup> , 9 <sup>th</sup> and 10 <sup>th</sup> mode. Positive frequency shift in 5 <sup>th</sup> mode combined with negative shift in 10 <sup>th</sup> mode.
<b>Higher Frequency Features (1000-3000hz)</b>	Small (~0.1hz), positive frequency shift in FRF around 1280hz. Positive displacement FRF around 2110hz. Higher, closer displacement FRF peaks around 2470hz.	Positive FRF peak around 1330hz. Inverse FRF displacement peaks from normal operations around 2450-2470hz.	Larger (~0.2hz), positive frequency shifts in FRF around 1280hz. Negative displacement FRF around 2110hz. Smaller, spread out displacement FRF peaks around 2470hz.
<b>Other Notes</b>	Generally closer to normal operating conditions in lower frequency spectrum – higher order FRF provides more features for this.	Relatively few features have been detected for identifying localisation in this region – however those features that are detected appear to be very distinct in nature.	This region exhibits large features, especially in the lower frequency spectrum. From these studies it appears easiest to determine the nature of an unbalance fault that falls in this region.

**Figure 20. Results summary table**

It can be noted from the above summary that the specific features identified are applicable only to the MFS (other machinery would not necessarily exhibit the same peak information and patterns shown here). However the methods of obtaining the results using FEA could easily be adapted to identify the features in alternative rotating machines. As FEA is now a common (and even integral) part of the design of rotating machines (for the identification of critical speeds and avoiding potential damage due to resonance), identifying the sections of the frequency spectrum which would provide for localisation feature detection should be a relatively straightforward task. This process could potentially be further speeded up by the application of model order reduction processes, with the reduction of FEA models to a system level model which enables simulations to be rapidly resolved. This in turn reduces the reliance on high powered computing facilities to solve highly detailed FEA models.

Current information gathering in the frequency domain from FEA models is often concentrated around the first few modes and critical speeds <sup>(6)</sup>, in order to identify potential resonances. The higher end of the spectrum is therefore often not looked at. It is therefore interesting to note from the results detailed above that no useful information for localisation detection was detected from the first four mode shapes, and useful information was gathered as high as 3000hz. The studies of the frequency spectrum

indicate that the few features higher than 3000hz were not useful for feature identification. The simple application of FRF across a wide spectrum could indicate the region in which useful information can be gathered, this enables more detailed investigations to be performed without the need to repeat this process many times over. Despite the discovery that features between 3000hz and 8000hz did not provide any useful information for unbalance localisation, it is worth noting that there were no FRF peaks displayed at all between 3500hz and 7000hz, after which a few small features were displayed once more. This indicates that as wide a frequency spectrum as possible should be considered at first in order to ensure all important features are identified, before the simulations are focussed on specific areas.

Another point that should be noted with regards to the results is the nature of the unbalance fault. In this case only pure unbalance has been considered (i.e. unbalance with no underlying cause). Although this case can happen in rotating machinery, it is also often possible for an unbalance to be caused by an underlining fault (such as an unbalance). In such a case, the frequency spectrum may be altered by the underlying fault, and it is therefore necessary to clarify the nature of the unbalance before localisation is undertaken. A number of methods exist in order to achieve this, including <sup>(7)</sup> and <sup>(8)</sup>.

Despite the relatively simple nature of the MFS, it was still possible to identify enough features in the frequency spectrum to provide a good indication of the location of unbalance faults. The position of the unbalance results in some distinct differences from both normal operating conditions and other unbalance positions. Whilst more complicated machinery would provide for more complex simulations (and processing time), further features would be expected to occur in the frequency spectrum. This would, in turn, increase the number of identifiable features for unbalance localisation – therefore improving the accuracy and reducing the error of the localisation process.

Once further point of note is the scale at which results are being measured. In the case of normal operating conditions (no fault) against faulty conditions, clear differences in mode shapes, modal frequencies and FRFs can be observed. The information is not so clear when attempting to localise the unbalance. As can be seen, shifts of 0.2-0.3hz have been used for unbalance localisation, and any lower frequency shift than this would be difficult to discern experimentally. This may cause difficulties in localising small unbalances, necessitating the need for as many features as possible to be identified in order to ensure accurate localisation.

As discussed, the potential use for the results is broad. The ability to determine with relative ease the approximate position of an unbalance fault in a gas turbine provides the potential for improved maintenance and safety. Simply identifying the ‘region’ of the unbalance could shorten any problem rectifying procedure noticeably. As an example, the ‘regions’ detailed for the 12 rotor MFS model could be used to represent the high, intermediate and low pressure sections of a gas turbine. The simulation and nature of the results performed in this paper do not require operational data for the machine in question; this therefore removes the need for extensive data collection (which is not always possible, depending on the application). The trade off for this is the requirement for extra simulations to be performed, preferably prior to machine operation.

Further studies, both in simulation and experimental validation may enable such information to be used in future to aid unbalance localisation studies from research into industry, as clear benefits at relatively low cost could be gained for the accurate prediction of such faults. By combining information similar to that gathered herein,

along with additional experimental studies to suit a particular case, (e.g. operational studies) there is the potential for unbalance to be localised within a machine to a relatively high degree of accuracy. Such information has potential applications in future IVHM solutions, and could even be adapted into onboard diagnostics and prognostic systems.

## 6. Conclusions

This paper outlined the localisation of unbalance faults through a simulation approach. High fidelity FEA models in NASTRAN have been created and validated experimentally using hammer testing alongside some operational analysis. The validated MFS model has then been used as the basis for studies of a 12 rotor system, with analysis having been performed in the region 0-8000hz. The analysis highlighted a useful frequency range for localisation studies of 0-3000hz. Within this, mode shapes and modal studies were performed along with frequency response functions in order to assist in localising unbalance faults into one of three regions (defined as 'front', 'middle' and 'rear' – loosely correlating to the high, intermediate and low pressure compressor sections of a gas turbine).

The results indicate the ability to estimate the location of an unbalance fault from static conditions using industry standard testing, thus providing the potential to improve maintenance procedures related to unbalance faults. Whilst the research is not all inclusive and the addition of extra simulation and experimental studies would improve accuracy and viability, the results provide a novel approach to tackling one of the most common rotordynamic faults beyond simple diagnosis.

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## **Appendix E**

### **Localizing Common Faults for Improved Aero Engine Maintenance**

#### **Reference:**

Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, "Localizing Common Faults for Improved Aero Engine Maintenance", *ASME International Mechanical Engineering Conference & Exposition*, ASME, Houston, November 2012, Publication Pending.

**IMECE2012-87610**

## LOCALIZING COMMON FAULTS FOR IMPROVED AERO ENGINE MAINTENANCE

**Walker, R.B.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
r.b.walker@cranfield.ac.uk

**Perinpanayagam, S.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
suresh.nayagam@cranfield.ac.uk

**Jennions, I. K.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
i.jennions@cranfield.ac.uk

### ABSTRACT

As industry moves towards implementing next generation Integrated Vehicle Health Management (IVHM) systems, the ability to quickly localize common faults in aero engines for improved maintenance is an important step in realizing this aim. Using a combination of high-fidelity finite element simulations and system level models, common unbalance faults have been studied for the purposes of localization. Looking at stationary and rotating vibration phenomena, features for fault localization have been identified and discussed from the perspective of implementation in future IVHM systems for rotating machinery. This includes studies into both the lower and the higher end of the frequency spectrum, looking at mode shapes, frequency response functions and forces at the bearing points in static conditions. Under rotating conditions, Campbell diagrams and transient analysis have been considered. In order to evaluate using the features identified, system level models have been created using Craig-Bampton reduction techniques, which are capable of recreating the studies conducted using the higher-fidelity finite element models. A discussion on introducing model based reasoning techniques to the system level model in order to adapt it for future IVHM systems are discussed. In turn, this leads to a discussion on a methodology for localizing faults in a wide range of rotating machines.

### INTRODUCTION

Unbalance faults are among the most commonly occurring [1] faults in rotating machinery. Many years of research has led to innovative methods of diagnosing such faults in both data driven and simulation domains. The recent work by [2] or [3] provide but two examples of recent work into this area.

Whilst many techniques exist for the detection of unbalance, a further aspect to this problem is the localization of unbalance within a complex system. With industry continuing to move towards more efficient condition based maintenance techniques, the accurate localization of faults is becoming a more pressing subject. Taking the airline industry as one example, the ability to transfer the knowledge that not only has a fault occurred but the precise nature of this fault and location within the engine would enable a faster turnaround time, decreased maintenance costs and more time in the air.

It is around these reasons that the research in this paper is being directed. Approaching the problem from an industry perspective, current in-field and on-board diagnosis and monitoring techniques are centered on the analysis of frequency domain data, often without using advanced processing techniques. The work contained herein has therefore been designed to aid information gathering for unbalance localization in industrial applications which do not rely on unique or novel algorithms for fault detection.

Recent research into unbalance faults in rotating machinery has taken place in both simulation and data-driven forms. Whilst both approaches have clear advantages, the continual need for experimental validation and verification combined with the power of modern simulation packages results in the need for a synergy between both domains when considering such problems. With this in mind, the localization studies in this paper are based upon a machine fault simulator (MFS) from Spectraquest. This enables a wide range of rotordynamic faults to be studied in a lab-based environment - including unbalance. With the MFS providing the basis of the studies, NASTRAN finite element software has been used in order to generate high fidelity finite element analysis (FEA) models. This approach enables localization studies to be performed using a higher number of rotors than can be fitted to the MFS, whilst providing

a base for validation and verification. A similar approach was conducted by [4] who used ANSYS FEA models to study damaged shafts, using the MFS as a base for studies. This previous work provided assistance with regards to constraints and validation of the NASTRAN model developed for the purposes of this paper. Validation takes the form of the industry standard approach of impact testing, combined with some operational comparisons of the MFS against the NASTRAN models.

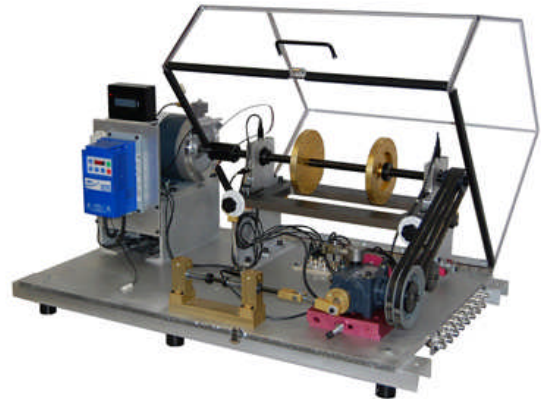
Using a successfully validated NASTRAN model, studies have been conducted of unbalance faults occurring throughout a 12 rotor system. The objective being to identify features which can be used to make observations as to the location of an unbalance fault within a system, and to provide this information in such a way that it can enhance the drive towards future integrated health management (IVHM) systems.

As new generations of commercial aircraft begin to enter service, the drive towards condition based maintenance has taken another step. Looking forward, next generation IVHM systems need to be based around an adaptable formula which can be applied to a wide range of designs and models [5]. Hence the requirement for a broad approach to unbalance fault localization.

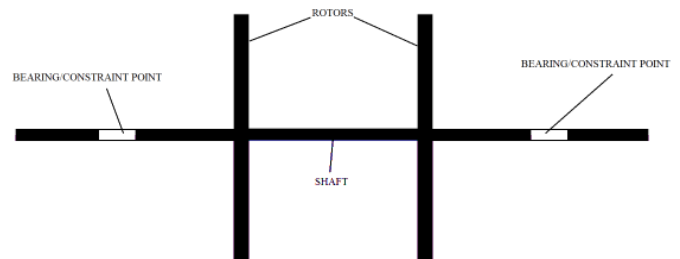
Due to the reasons detailed above, the research detailed in this paper has been split into four sections. The first deals with the construction of high fidelity finite element models of the MFS. This section also deals with model validation using impact testing alongside other validation methods. Following on from this, low order feature identification has been performed. This section covers the first ten modes of the MFS, detailing features identified which could be relevant to the localization of unbalance faults. Higher-order frequency domain features are studied in order to investigate the frequency range for which useful features can be identified, and in order to identify further features for use in fault localization. Finally, rotational studies have been performed – including construction of Campbell diagrams and transient analysis in order to complete the localization study.

## HIGH-FIDELITY SIMULATIONS

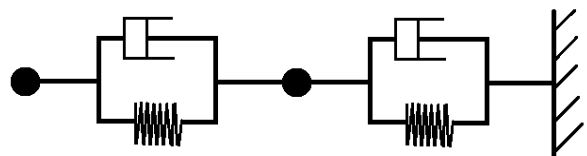
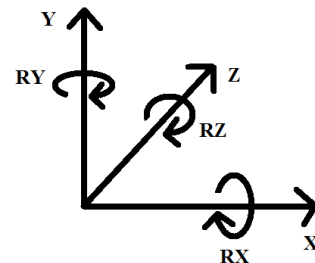
This paper builds upon the detailed work by [4], which identifies a system of model parameters and constraints for a finite element simulation of the MFS. For the purposes of this paper, the same constraint system has been applied to a NASTRAN model (as opposed to ANSYS used by [4]). Additional developments have been made in an attempt to assist the validity and validation of the model. This includes the application of accurate geometry in the model, along with slight dimensional alterations in order to configure the model to the set-up of the particular MFS to be used for validation. The MFS can be seen detailed in fig. 1. Fig. 2 details the model set developed for validation and localization studies, whilst fig. 2.3 demonstrates the coordinate system and constraint type used in the model validation.



**Fig. 1: Spectraquest MFS**



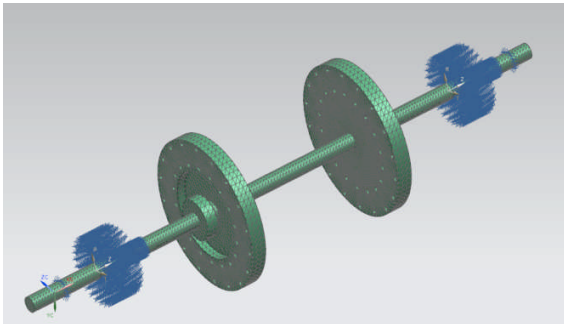
**Fig. 2: MFS FEA Sketch**



**Fig. 3: Coordinate and Constraint System**

In order to correctly simulate the setup of the MFS in NASTRAN, the constraint system detailed in previous literature has been altered. In this case five degrees of freedom have been fixed (X, Y, RY, Z and RZ). In the manner shown in fig. 3 (from [4]). The final degree of freedom (RX) is not a fixed constraint; however it has a stiffness/damping value assigned to mimic the role of the bearing points in the system. This constraint system

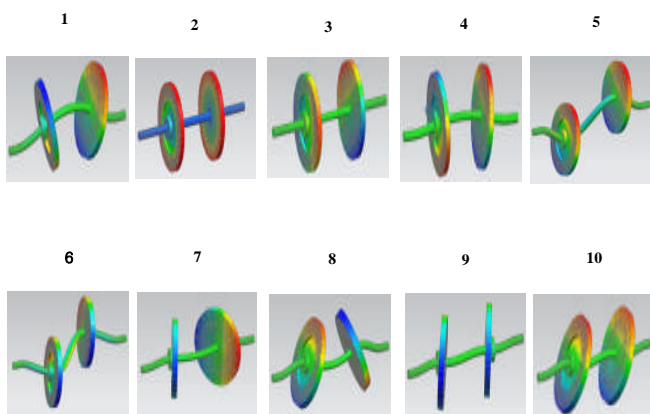
was refined through a series of trial and error experimental validation studies. The geometrically accurate, meshed and constrained finite element model can be seen in fig. 4



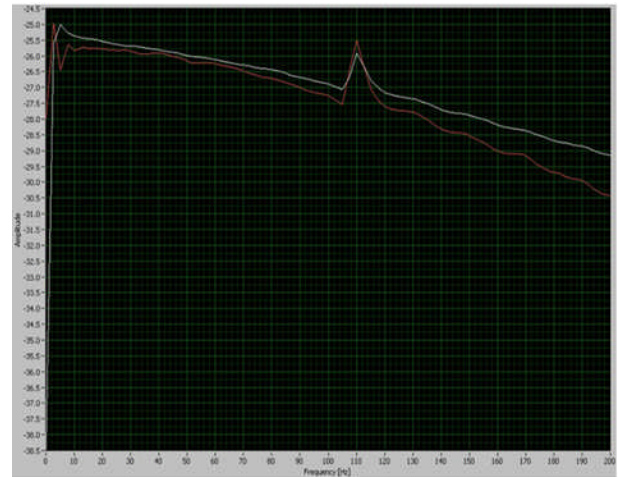
**Fig. 4:** Constrained and Meshed NASTRAN Model

Using this refined model of the MFS rotor and shaft system, the first 10 mode shapes were investigated for comparison against previous work in literature and for the purposes of experimental validation. The differences from the work performed by [4] can be attributed to different geometry along with the adjusted constraint system. Despite this, the results are largely coherent with those previously performed. In order to validate the model, hammer testing was performed for a frequency range covering the first 10 modes (in the case of the MFS, 0-1000hz). In this case, the identification of the modal frequencies was identified by clear peaks in the frequency spectrum, occurring at or near those frequencies predicted by the simulation. The mode shapes could then be affirmed by movement of the accelerometer along the length of the shaft to identify nodes and anti-nodes.

This validation procedure has been completed for both free-free and fixed-fixed setups (free standing system and fixed in the bearing points respectively). In fig. 5, the first 10 mode shapes can be seen as defined by the NASTRAN simulation. An example hammer test is displayed in fig. 6.



**Fig. 5:** First 10 mode shapes of the MFS



**Fig. 6:** Example hammer test results

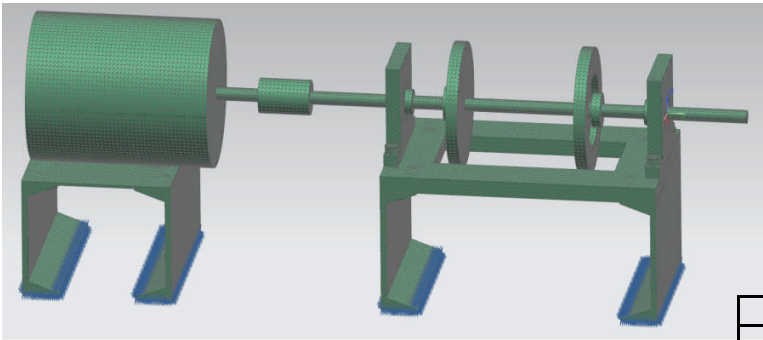
In fig. 6, a clear peak can be seen which indicates the first modal frequency at 110 Hz. In this case two accelerometers are attached in the nodal position in the center of the shaft. This procedure was repeated from 0-1000Hz, with the results summarized in tab. 1. This table indicates the comparisons between the simulation results from the final NASTRAN model and the hammer testing. It can be seen that slight variation exists between the model and the hammer test. It is also relevant that the simulation predicted 'double' modes, which it is difficult to distinguish between on the hammer test. It is also often the case that not all modes predicted by simulation appear to be present during experimental tests. In this case, mode 2 and 3 were not distinguishable on the hammer test. Aside from this, the simulation results appear to be sufficiently valid in order to undertake further testing using the NASTRAN model.

Mode Number	NASTRAN NX (Hz)	Fixed-Fixed Hammer Test (Hz)
1	112.4	110
2	157.9	Not detected
3	158.0	Not detected
4	196.2	192
5	360.1	353
6	360.1	353
7	581.8	580
8	581.9	580
9	635.3	640
10	635.4	640

**Tab. 1:** Simulation and Experimental Hammer Test Comparison

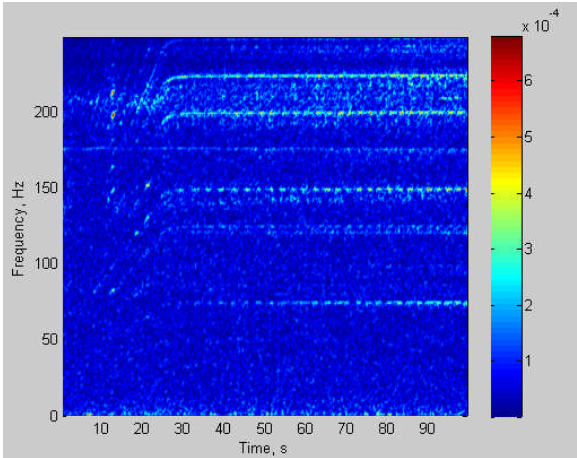
Further simulation for the purposes of evaluation included the study of structural modes, along with some operational validation of the results. In order to study the structural modes

of the system, and identify some features present in the hammer test, a larger model of the MFS was constructed, detailing the full shaft and coupling, electric motor, bearings, mountings and base supports. This model can be viewed in fig. 7. Whilst such a complex system with a wide variety of materials provided for a model which was not capable of simulating the whole range of modal frequencies present in the system; it is capable of indicating some of the more prominent structural modes.



**Fig. 7:** Full MFS Structural Model

These structural modes indicated from the model in fig 7 were used in order to understand in more detail some of the phenomena detected when the MFS is in operation. The next stage of model validation involved the addition of an unbalance fault to the MFS and the corresponding NASTRAN models. This takes the form of a small weight screwed into the periphery of the rotor (for the validation experiments, a small unbalance was added in the same position to both rotors). In order to experimentally validate the application of the unbalance faults, spectrograms were obtained from the MFS in operation at 25hz (an example plot is given in fig. 8). Using the information obtained from the simulations, the operational modes at 25hz could be isolated from the structural modes and other phenomena. The shift in modal frequency due to the addition of the unbalance fault could then be compared for experimental results. All experimental results were obtained using NI Labview hardware and software, with accelerometers mounted on the bearing housing. The mass of the unbalance weight was 5.3g. The results from these comparisons can be seen in fig. 9.



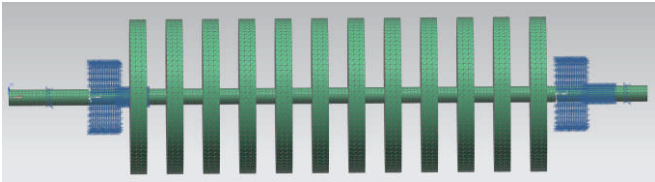
**Fig. 8:** Waterfall plot from MFS operation at 25Hz

Mode:	1	2	3	4	5	6	7	8	9	10
Unbalance Mode Shift from Normal (Experimental )	1.16	N/A	N/A	2.7	8.9	4.8	2.5	1.4	4.8	4.0
Unbalance Mode Shift from Normal (Simulation)	1.0	1.9	1.5	3.0	8.6	4.4	3.4	3.0	4.9	3.6

**Fig. 9:** Simulation and experimental results for machine operation at 25Hz

### LOW-ORDER FEATURE IDENTIFICATION

With the two rotor MFS models judged to be validated to a sufficient degree, a new NASTRAN model was created for the study of unbalance localization. Taking the same shaft dimensions and constraint system as the validated model, twelve equally-spaced rotors were placed on the simulation. The revised model was run with no faults induced, followed by a 5.3g (to mimic the standard unbalance that can be applied to the MFS) unbalance weight applied to each of the 12 rotors in turn. The 12 rotor meshed model can be seen in fig. 10.



**Fig. 10:** 12 Rotor Model

Some of the results of the simulation can be seen in fig. 11. This graph displays the shift in frequency, calculated in Hz, from normal (no fault) conditions. ‘Rotor 1’ indicates the rotor positioned closest to the motor, ‘rotor 12’ indicates the rotor farthest from the motor. It is important to note that, whilst the



rotors are balanced, they are not symmetrical due to the rotor to shaft coupling. Repeat runs, along with a conservative calculation of the inherent error in the model indicates that the results displayed are subject to  $\pm 1$  Hz.

Incorporating this error into the results produces the summary in tab. 2. In this case, highlighted cells indicate ‘useful’ information (or a confirmed shift in modal frequency above the model error level). The information displayed in the table indicates that in this case no useful information can be gathered from the first four mode shapes. The remaining modes give some information useful for the localization of unbalance, however further studies were required in order to compliment this data. The data displayed in tab. 2 is also inconclusive with regards to rotor numbers three, five and eleven. It is also of note that similar trends can be seen in rotor two and rotor seven. It is for these reasons that a larger range of the frequency spectrum needs to be looked at.

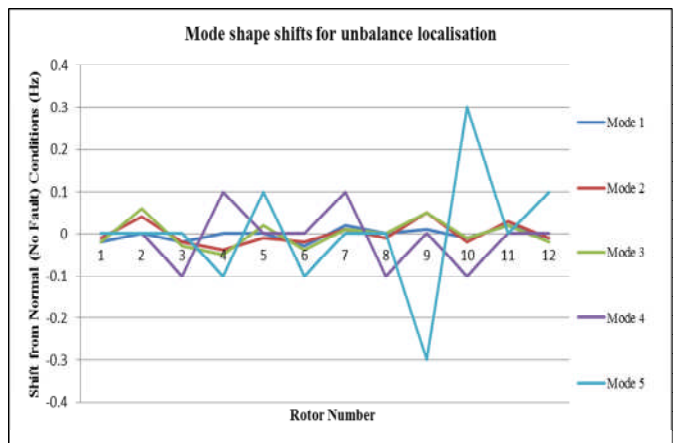


Fig 11: Mode Shape Shifts

excitation force at the center point of the shaft and measures the force response at the center of the bearing point closest to the motor. The frequency range 0-1000Hz was studied, however useful information was found to be within the range 0-300Hz, which is displayed in fig. 12. In this it can be seen that the higher response is displayed from the rotors farthest from the motor, whilst the rotors placed closer to the motor display a smaller force response.

In this case, rotor 10 can be seen to exhibit the highest peak amplitude response, whilst rotor 2 exhibits the lowest. The rotors placed in the center of the shaft exhibit a similar response to the normal operating condition, making identification difficult. Therefore, whilst assessing the force response at the bearing points provides a useful addition to a potential localization strategy, in this case it does not provide a stand-alone solution.

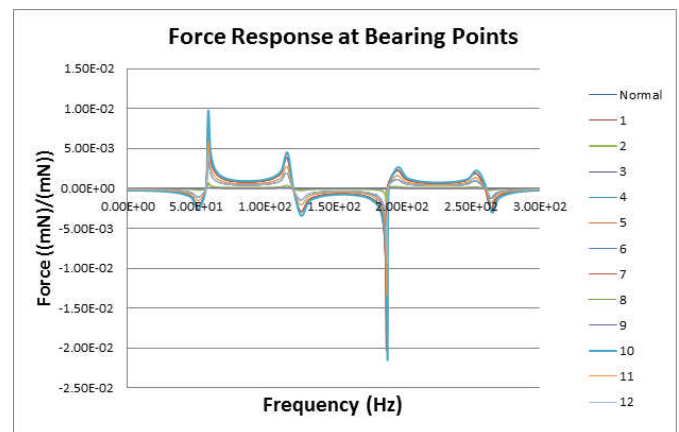


Fig. 12: FRF at Bearing Points

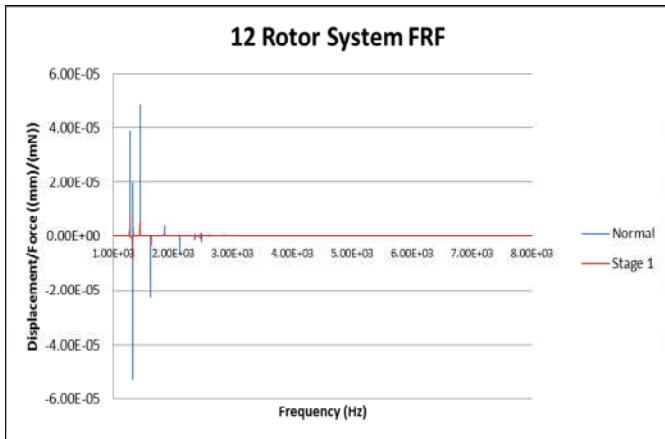
## HIGH-ORDER FEATURE IDENTIFICATION

With the need to look at further details of the frequency spectrum having been outlined, an alternative method of analyzing the spectrum was required. At frequencies above 1000 Hz, assessing the mode shapes of the system can become difficult due to the complex motions encountered at higher modes. In addition, it is useful to provide an alternative (yet still relatively simple) method of picking features for localization of the unbalance fault. Therefore, the frequency response function has been calculated across the 12 rotor model. A range of simulations was run in order to determine the optimum input and output positions for the FRF, eventually determining that a point on the center of rotor 1 provided for the optimum input, with the same point on rotor 12 being used for the output. These points were chosen due to the clarity of output results provided. The range chosen for the frequency spectrum was 1000-8000hz. This continues from the lower-order frequency studies done, and continues up until the maximum point at which validation by hammer test is possible. This was deemed to be a wide enough frequency range for testing, inside which the useful frequency features could be identified. The results of the simulation can be seen in fig. 13.

	Roto r 1	Roto r 2	Roto r 3	Roto r 4	Roto r 5	Roto r 6	Roto r 7	Roto r 8	Roto r 9	Roto r 10	Roto r 11	Roto r 12
Mode 1	-	-	-	-	-	-	-	-	-	-	-	-
Mode 2	-	-	-	-	-	-	-	-	-	-	-	-
Mode 3	-	-	-	-	-	-	-	-	-	-	-	-
Mode 4	-	-	-0.1 Hz	+0.1 Hz	-	-	+0.1 Hz	-0.1 Hz	-	-0.1 Hz	-	-
Mode 5	-	-	-	-0.1 Hz	+0.1 Hz	-0.1 Hz	-	-	-0.3 Hz	+0.3 Hz	-	-
Mode 6	-	+0.1 Hz	-	-0.2 Hz	+0.1 Hz	-	-	-	-	-	-	-
Mode 7	-0.2 Hz	+0.1 Hz	+0.1 Hz	-	-	-0.2 Hz	-	+0.1 Hz	+0.1 Hz	-0.1 Hz	-0.1 Hz	-
Mode 8	-0.2 Hz	+0.2 Hz	+0.1 Hz	-0.3 Hz	-	+0.2 Hz	-0.2 Hz	-0.1 Hz	+0.2 Hz	+0.1 Hz	-0.1 Hz	-0.2 Hz
Mode 9	-0.1 Hz	-	-	-0.2 Hz	-	+0.2 Hz	-	-0.4 Hz	+0.3 Hz	-	-	+0.1 Hz
Mode 10	-	+0.1 Hz	-0.1 Hz	-	+0.1 Hz	-0.2 Hz	+0.1 Hz	-0.1 Hz	+0.2 Hz	-0.2 Hz	+0.1 Hz	-

Tab 2: Mode Shape Summary Table

Following on from the study of mode shape shifts, the force response at the bearing points has been studied. This takes an



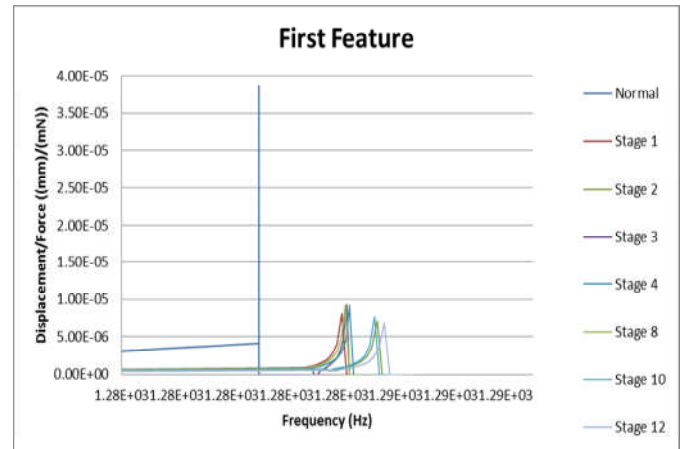
**Fig 13: FRF Overview**

In fig. 13 the whole frequency spectrum can be seen from 1000 to 8000 Hz for normal operating conditions and unbalance applied to the first stage. This overview indicates that the useful information contained in the system is concentrated between 1000 Hz and 3500 Hz. Further to this, as the differences between the different rotors are difficult to establish, focusing on each peak in the spectrum is required in order to extract any relevant information.

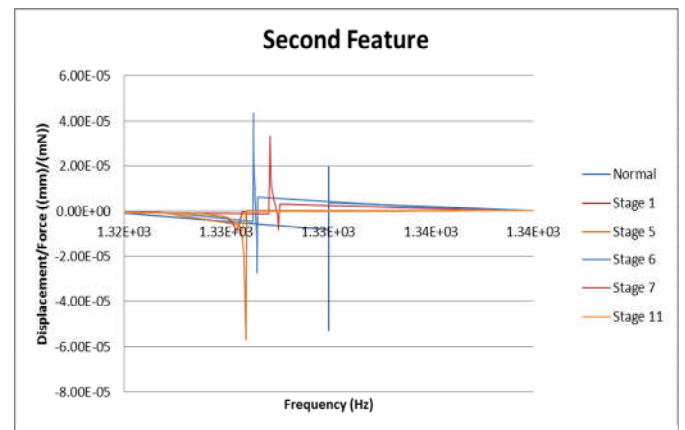
In fig. 14, a close examination of the first peak on fig. 13 can be seen. In this case the difference between normal and the faults conditions is clear. The difference between the peaks of the faulty conditions is more difficult to distinguish, however it can be noted that the peaks of the first six stages of the system are placed lower in the frequency spectrum than the last six stages of the system, the peaks of which reside further up the frequency spectrum.

In fig. 15, the second peak can be seen in close up. This again demonstrates a large difference between faulty and normal operating conditions. From this it can be seen that the positive peaks indicate the two rotors in the center of the shaft (6 and 7), all other peaks can be seen to be negative. The information that can be gathered from the next peak (fig. 16) is not as clear, however it can be noted that rotor 4 and 10 experience a large positive displacement, whilst 3 and 9 are the only rotors to produce negative displacements in the FRF when an unbalance weight is applied to the rotors. The next two peaks in the spectrum do not exhibit any interesting behavior, however around 2100 Hz the peak in fig. 17 can be seen to indicate larger positive displacement peaks for the six rotors positioned closest to the motor than the six rotors positioned further away. After this point in the simulation, the amplitude of the displacement peaks diminishes somewhat. However, an interesting sequence of features can be seen in fig. 17. In this case, another difference can be viewed between those rotors at the motor end of the shaft (1-6) as opposed to those away from the motor end (8-12). In the case of rotor 7 (which is directly in the center of the shaft due to the slightly offset dimensions), a

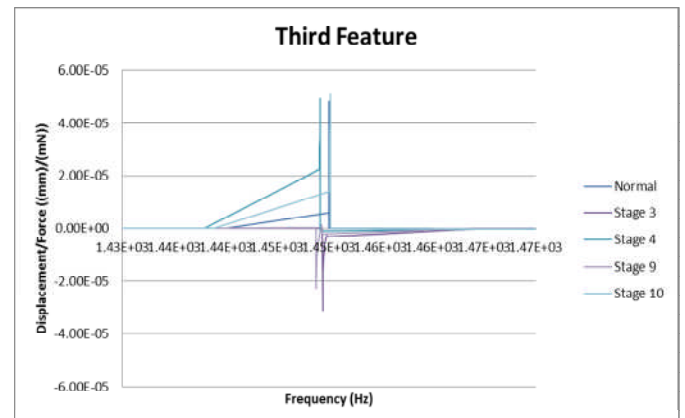
unique pattern can be seen, with inverse direction peaks in the  $2.43 \times 10^{-3}$  to  $2.47 \times 10^{-3}$  region.



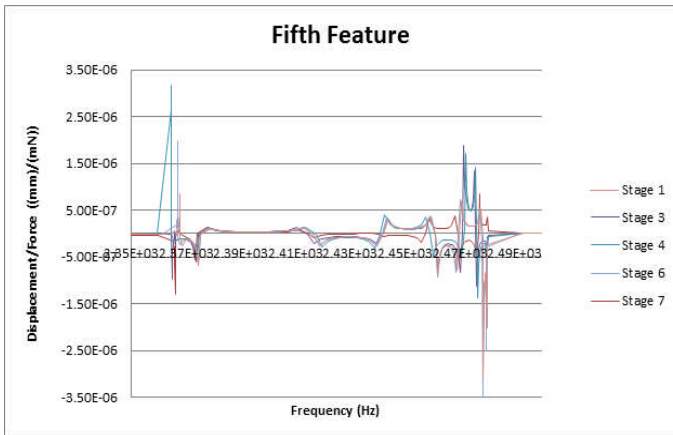
**Fig 14: FRF 1<sup>st</sup> Feature**



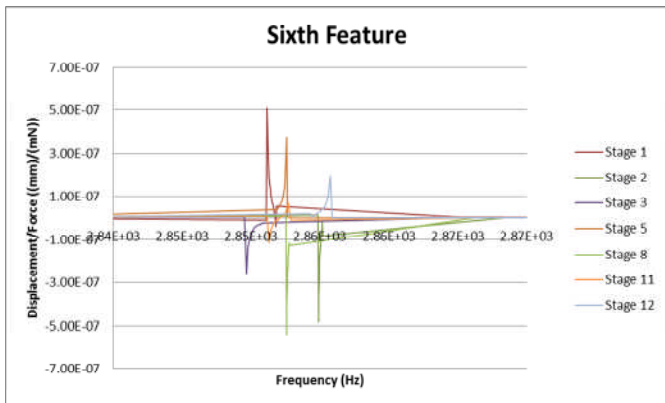
**Fig. 15: FRF 2<sup>nd</sup> Feature**



**Fig. 16: FRF 3<sup>rd</sup> Feature**



**Fig. 17: FRF 5<sup>th</sup> Feature**



**Fig. 18: FRF 6<sup>th</sup> Feature**

The final point of interest is displayed in fig. 18, in this case it can be seen that the rotors at either end of the shaft experience positive displacement (1, 11 and 12), whilst the others (aside from normal, non-fault condition) experience a negative displacement. After these points, the remaining frequency spectrum measured (~3000-8000 Hz) exhibits relatively few features, the amplitude and nature of which make the remaining results inconclusive. From the information gathered, analysis can be performed to provide recommendations for unbalance localization.

## ROTATIONAL LOCALISATION STUDIES

Following on from the static studies, the rotational state of the MFS required investigation. The first stage in this is the analysis of Campbell Diagrams – a common analysis tool for rotating machinery. In this case, the Campbell Diagrams have been solved using a complex eigenvalue analysis within NASTRAN, and plotted with a rotating reference frame. For such a case, forward critical speeds are indicated where frequency = 0Hz, whilst backward critical speeds are indicated where modes intersect 2P.

In fig. 19, the first 10 modes can be seen for the 12 rotor localization model, with no applied fault (normal operating conditions). This figure is displayed in order to demonstrate the

predicted response of such a system. In fig. 20, the first forward and the first backward whirl is displayed for each unbalance condition (unbalance weight applied to each rotor in turn). It can be seen that, at lower RPM, the difference between unbalance conditions is relatively small (although it is visible). As the rotation speed increases, the differences between the unbalance positions increase to the extent that very different critical speeds can be seen. It is however of note that the maximum speed for the MFS is 6000 RPM (for short durations of time). In this case, the differences between unbalance conditions become more obvious as the first critical speed is approached, or around maximum speed for the MFS. It is also worth noting that the differences between unbalance conditions are generally much larger whilst the machine is rotating, as opposed to the static condition. However, if a machine has an unbalance fault, gathering data whilst operating (especially at high speed) could be undesirable and unsafe, leading to a trade off with using rotating data for localization.

The information contained in fig. 20 is important as the first forward and backward whirl modes provide the only critical speeds which could be reached within the operational window of the MFS. These critical speeds occur around 5000 Hz. Although it is not possible (and indeed dangerous) to run a faulty machine at the critical speed, it can be noted that larger differences in the modes of the system can be identified shortly after these critical speeds have been surpassed. The backward whirl in particular appears to diverge dramatically around the maximum speed of 6000 rpm. In the case of the MFS, running at maximum speed is only possible for a short period of time, and is not recommended for high unbalance conditions.

Relating this scenario to aircraft gas turbines (as an example), a period of operation at full thrust commonly occurs during the take-off phase of each flight. In order to aid the localization of faults, collecting vibration data during this phase of the flight would potentially provide the best option for identifying strong features.

For the purposes of clarifying the information from fig. 20, fig. 21 displays the same comparison again, however limited to the operational window of the MFS. It can be seen from this information that large differences exist in the first critical speeds for the forward whirl if the unbalance is located on the rotors father from the motor end. This separation from normal operating conditions can be seen to occur around 3000rpm, well within the operational range of the MFS, however they become much more pronounced around the critical speeds. When the unbalance is placed on the rotors closer to the motor end, larger separation can be observed in the backward whirl case. However, this information is more difficult to come by as it exists in a higher RPM range.

Fig. 22 displays the second forward and backward whirl modes, again for each unbalance condition. In this case, large differences can again be seen at high RPM values, with significant differences in the critical speeds. At speeds around 6000 RPM, the differences between unbalance conditions are much greater than at static conditions. This leads to improved



localization of unbalance, however – once an unbalance fault has been detected, it is undesirable to continue running a rotating machine around the maximum RPM values. The results from the Campbell diagrams indicate the potential to localize faults using data gathered from rotating systems. However the nature of this requires that data be collected during normal operation be collected – as collecting the data required for localization after unbalance faults have been identified is not a practical method of data collection.

The higher modes (not displayed in this paper), contain additional differences between the different unbalance faults. However, as these mostly occur above the operational range of the machine they have been omitted from this study. It is also worth noting that during the design of turbo machinery, simulating Campbell diagrams are an important part of the design process. This is due to the potential danger posed by critical speeds and the need to work around these operating speeds. As a result, adapting such simulations to cover predetermine localization criteria should be possible for most applications. The MFS is a relatively simple setup, however in more complicated machinery (especially with higher operating speeds), a larger number of modes would provide additional opportunities for localizing faults.

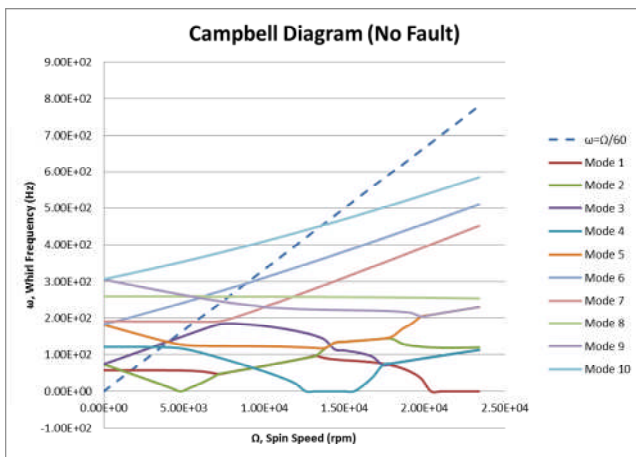


Fig. 19: Campbell Diagram

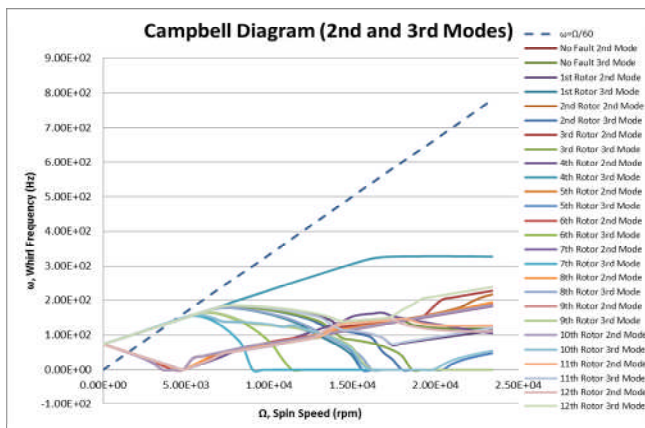


Fig. 20: Campbell Diagram

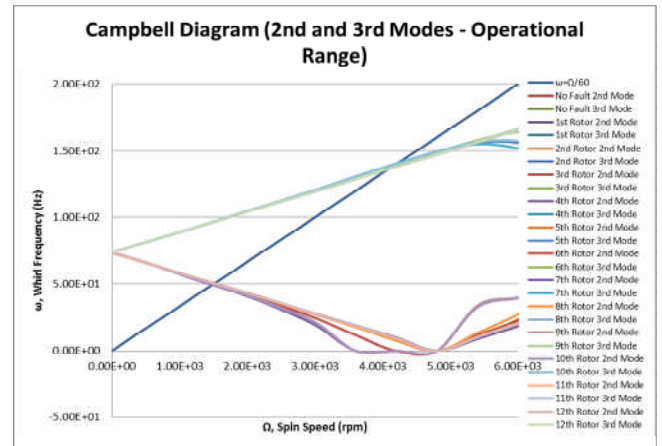


Fig 21: Campbell Diagram

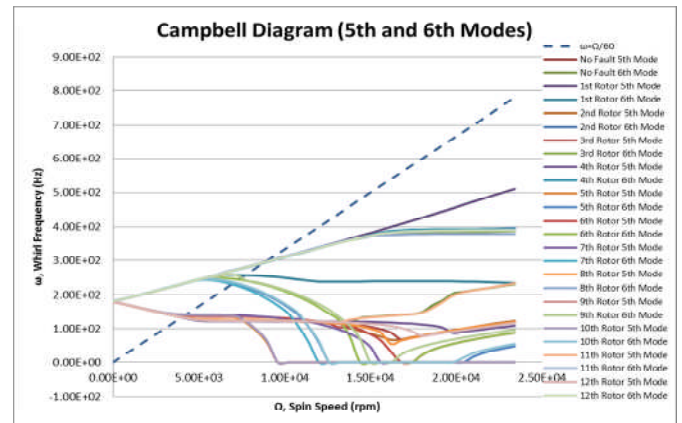


Fig 22: Campbell Diagram

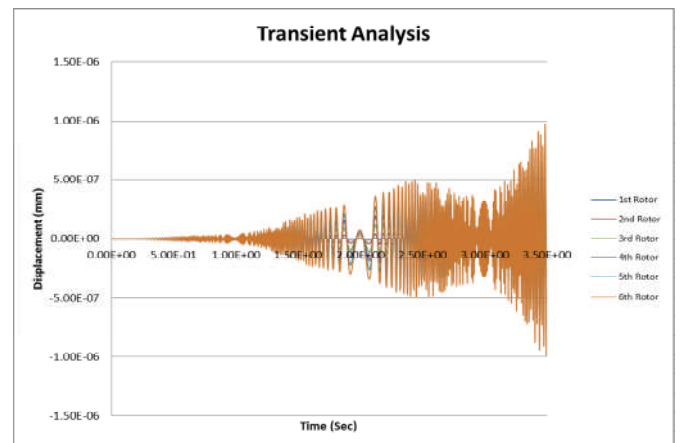


Fig. 23: Transient Analysis

In addition to the Campbell Diagrams, transient response analysis has been performed in order to study the run up conditions of the MFS with unbalance faults. Run-up, run-down tests are a common method of conducting ‘pass off’ tests in

rotating machines, and as such any useful features for the identification and localization of faults which can be determined. A range of speeds acceleration values were studied, all yielding similar results. In fig. 23, a typical transient response can be seen for the localization model. In this case, a linear acceleration from 0-1000RPM over a 3.5 second period is shown, with the response detailed for each unbalance case. The unbalance has been applied as a sinusoidal sweep load function about a node placed on the shaft centerline for each rotor in turn. There is, however, a noticeable difference in amplitude of vibration, with the larger vibration signatures appearing for the rotors in the center of the shaft, perhaps influenced by the damping effect of the rotors closer to the bearing points. This information adds another small fact to the list for localizing faults, however – as each engine will display its own unique vibration signatures, in order to obtain useful information from any transient response type analysis a good understanding of the baseline (normal) operating conditions from a recent run would be required in order to interpret any meaningful data.

## DISCUSSION

The results collected across a broad frequency range represent data which can be collected with relative ease from a wide range of rotating machines. As previously stated, this allows for localization recommendations to be adapted to a number of different applications. Whilst a 12 rotor system was used for the purposes of studying the unbalance fault as it was placed in different positions down the length of the shaft, in order to summarize the results and provide suitable conclusions the localization it is to be divided into three ‘regions’.

	Unbalance in Forward Region (Rotor 1-4)	Unbalance in Middle Region (Rotor 5-8)	Unbalance in Rear Region (Rotor 9-12)
<b>Lower Frequency Features (0-1000hz)</b>	Negative shift in 7 <sup>th</sup> and 8 <sup>th</sup> modal frequencies. Positive shift in 8 <sup>th</sup> modal frequency only. Negative shift in 6 <sup>th</sup> , 8 <sup>th</sup> and 9 <sup>th</sup> Modal Frequencies. Low force response at bearing points	Frequency shifts in modes 7-10. Distinct frequency shift in 9 <sup>th</sup> mode only.	Distinct frequency shifts in 5 <sup>th</sup> , 8 <sup>th</sup> , 9 <sup>th</sup> and 10 <sup>th</sup> mode. Positive frequency shift in 5 <sup>th</sup> mode combined with negative shift in 10 <sup>th</sup> mode. High response at bearing points
<b>Higher Frequency Features (1000-3000hz)</b>	Small (~0.1hz), positive frequency shift in FRF around 1280hz. Positive displacement FRF around 2110hz. Higher, closer displacement FRF peaks around 2470hz.	Positive FRF peak around 1330hz. Inverse FRF displacement peaks from normal operations around 2450-2470hz.	Larger (~0.2hz), positive frequency shifts in FRF around 1280hz. Negative displacement FRF around 2110hz. Smaller, spread out displacement FRF peaks around 2470hz.
<b>Rotating Features</b>	Significant localization features close to maximum operational RPM limit.	High amplitude of vibration under transient analysis (run up) conditions.	Significant localization features close to maximum operational RPM limit.
<b>Other Notes</b>	Generally closer to normal operating conditions in lower frequency spectrum – higher order FRF provides more features for this.	Relatively few features have been detected for identifying localization in this region – however those features that are detected appear to be very distinct in nature.	This region exhibits large features, especially in the lower frequency spectrum. From these studies it appears easiest to determine the nature of an unbalance fault that falls in this region.

**Tab. 3:** Summary Table

These regions are to be ‘forward’, ‘middle’ and ‘rear’, and refer to rotors 1-4, 5-8 and 9/12 respectively. This approach groups the results such that it is possible to predict with greater accuracy the portion of the machine in which the fault has occurred.

With the three regions defined, the results discussed in this paper can be detailed in tabular format, as detailed in tab. 3.

It can be noted from the above summary that the specific features identified are applicable only to the MFS (other machinery would not necessarily exhibit the same peak information and patterns shown here). However the methods of obtaining the results using FEA could easily be adapted to identify the features in alternative rotating machines. As FEA is now a common (and even integral) part of the design of rotating machines (for the identification of critical speeds and avoiding potential damage due to resonance), identifying the sections of the frequency spectrum which would provide for localization feature detection should be a relatively straightforward task. This process could potentially be further speeded up by the application of model order reduction processes, with the reduction of FEA models to a system level model which enables simulations to be rapidly resolved. This in turn reduces the reliance on high powered computing facilities to solve highly detailed FEA models.

Current information gathering in the frequency domain from FEA models is often concentrated around the first few modes and critical speeds [6], in order to identify potential resonances. The higher end of the spectrum is therefore often not looked at. It is therefore interesting to note from the results detailed above that no useful information for localization detection was detected from the first four mode shapes, and useful information was gathered as high as 3000 Hz. The studies of the frequency spectrum indicate that the few features higher than 3000 Hz were not useful for feature identification. The simple application of FRF across a wide spectrum could indicate the region in which useful information can be gathered, this enables more detailed investigations to be performed without the need to repeat this process many times over.

Despite the discovery that features between 3000 Hz and 8000 Hz did not provide any useful information for unbalance localization, it is worth noting that there were no FRF peaks displayed at all between 3500 Hz and 7000 Hz, after which a few small features were displayed once more. This indicates that as wide a frequency spectrum as possible should be considered at first in order to ensure all important features are identified, before the simulations are focused on specific areas.

Another point that should be noted with regards to the results is the nature of the unbalance fault. In this case only pure unbalance has been considered (i.e. unbalance with no underlying cause). Although this case can happen in rotating machinery, it is also often possible for an unbalance to be caused by an underlining fault (such as an unbalance). In such a case, the frequency spectrum may be altered by the underlying

fault, and it is therefore necessary to clarify the nature of the unbalance before localization is undertaken. A number of methods exist in order to achieve this, including [7] and [8]. Despite the relatively simple nature of the MFS, it was still possible to identify enough features in the frequency spectrum to provide a good indication of the location of unbalance faults. The position of the unbalance results in some distinct differences from both normal operating conditions and other unbalance positions. Whilst more complicated machinery would provide for more complex simulations (and processing time), further features would be expected to occur in the frequency spectrum. This would, in turn, increase the number of identifiable features for unbalance localization – therefore improving the accuracy and reducing the error of the localization process.

From the studies into rotating conditions, it is clear that localization features become more pronounced at higher RPM values. Whilst this improves the potential of localizing faults, there are risks of unsafe operation and damage whilst operating machinery at high speed with an identified fault. For this reason, it is important that data is collected and sampled during routine machine operation in order that this data can be analyzed after the fault has been positively identified. Data collected from static studies could then be used to supplement/confirm the estimated location of the fault before investigative maintenance procedures are carried out.

Once further point of note is the scale at which results are being measured. In the case of normal operating conditions (no fault) against faulty conditions, clear differences in mode shapes, modal frequencies and FRFs can be observed. The information is not so clear when attempting to localize the unbalance. As can be seen, shifts of 0.2-0.3hz have been used for unbalance localization, and any lower frequency shift than this would be difficult to discern experimentally. This may cause difficulties in localizing small unbalances, necessitating the need for as many features as possible to be identified in order to ensure accurate localization, and necessitating the need for regular operational data to be collected for the best chance of localization.

As discussed, the potential use for the results is broad. The ability to determine with relative ease the approximate position of an unbalance fault in a gas turbine provides the potential for improved maintenance and safety. Simply identifying the ‘region’ of the unbalance could shorten any problem rectifying procedure noticeably. As an example, the ‘regions’ detailed for the 12 rotor MFS model could be used to represent the high, intermediate and low pressure sections of a gas turbine. The simulation and nature of the results performed in this paper do not require operational data for the machine in question; this therefore removes the need for extensive data collection (which is not always possible, depending on the application). The tradeoff for this is the requirement for extra simulations to be performed, preferably prior to machine operation.

Further studies, both in simulation and experimental validation may enable such information to be used in future to aid unbalance localization studies from research into industry, as clear benefits at relatively low cost could be gained for the accurate prediction of such faults. By combining information similar to that gathered herein, along with additional experimental studies to suit a particular case, (e.g. operational studies) there is the potential for unbalance to be localized within a machine to a relatively high degree of accuracy. Such information has potential applications in future IVHM solutions, and could even be adapted into onboard diagnostics and prognostic systems.

## CONCLUSIONS

This paper outlined the localization of unbalance faults through a simulation approach. High fidelity FEA models in NASTRAN have been created and validated experimentally using hammer testing alongside some operational analysis. The validated MFS model has then been used as the basis for studies of a 12 rotor system, with analysis having been performed in the region 0-8000hz. The analysis highlighted a useful frequency range for localization studies of 0-3000hz. Within this, mode shapes and modal studies were performed along with frequency response functions in order to assist in localizing unbalance faults into one of three regions (defined as ‘front’, ‘middle’ and ‘rear’ – loosely correlating to the high, intermediate and low pressure compressor sections of a gas turbine. In addition to static studies, rotational simulations have been performed which indicate the need for data to be collected during routine machine operation for the best chance to localize faults.

The results indicate the ability to estimate the location of an unbalance fault from static and rotating conditions using industry standard testing, thus providing the potential to improve maintenance procedures related to unbalance faults. Whilst the research is not all inclusive and the addition of extra simulation and experimental studies would improve accuracy and viability, the results provide a novel approach to tackling one of the most common rotordynamic faults beyond simple diagnosis.

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## **Appendix F**

### **Localizing Unbalance Faults in Gas Turbines**

#### **Reference:**

Walker, R., Perinpanayagam, S., Jennions, I. K., 2012, "Localizing Unbalance Faults in Gas Turbines", *ASME Turbo Expo 2013*, ASME, San Antonio, June 2013, Publication Pending.

**GT2013-94455**

## **LOCALIZING UNBALANCE FAULTS IN ROTATING MACHINERY**

**Walker, R.B.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
r.b.walker@cranfield.ac.uk

**Perinpanayagam, S.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
suresh.nayagam@cranfield.ac.uk

**Jennions, I. K.**  
IVHM Centre  
Cranfield University  
Cranfield, Bedfordshire, UK  
i.jennions@cranfield.ac.uk

### **ABSTRACT**

Excessive levels of unbalance in rotating machinery continue to contribute to machine downtime and unscheduled and costly maintenance actions. Whilst unbalance as a rotordynamic fault has been studied in great detail during the last century, the localization of unbalance within a complex rotating machine is today often performed in practice using little more than ‘rules of thumb’. In this work, localizing excessive unbalance has been studied from an experimental perspective through the use of two rotordynamic test rigs fitted with multiple disks. Sub-synchronous non-linear features in the frequency domain have been identified and studied as a method of aiding the localization of unbalance faults, particularly in situations where sensor placement options are limited. The results of the study are discussed from the perspective of next-generation Integrated Vehicle Health Management (IVHM) systems for rotating machines.

### **INTRODUCTION**

Unbalance as a fault is among the most commonly occurring faults in rotating machinery [1]. All rotating machines contain an inherent amount of unbalance, and therefore operate after balancing has been performed in order to bring this to within a given tolerance. The fault ‘unbalance’ can therefore be considered as an unbalance occurring outside of this given tolerance. Such conditions can be caused by a wide variety of phenomena. Taking the example of a gas turbine, unbalance may be caused by a buildup of material on compressor or turbine disks, blade damage (ranging from small cracking/chipping to full blade-off) and incorrect/inaccurate maintenance/balancing procedures - to name but three examples.

Modern day rotating machines operate with a high level of reliability, and yet the drive for ever increased operation and decreased unscheduled maintenance is providing additional

challenges for industry. The airline industry provides a current example of this desire, with airlines pushing manufacturers to enable shorter turnaround times and to keep aircraft in the air longer, increasing cost benefit [2]. Despite the high level of reliability, unbalance, along with other rotordynamic faults, remains an aspect which requires consideration in this drive for increased reliability and improved maintenance procedures [3]. The accurate localization of unbalance within a complex rotating machine (such as a gas turbine) has the potential to improve maintenance by enabling technicians to attend directly to the point of the fault. Boroscopy and rebalancing rotating machinery can be a time consuming and intrusive process, and as such even the ability to localize unbalance between the high pressure compressor, low pressure compressor or turbine portions of a rotating machine can bring benefits to the maintenance procedure. Upon the accurate localization of unbalance, traditional multi-plane balancing methods may be applied in order to correct the fault (dependent on the root cause of the unbalance).

Studies on unbalance in rotating machines are numerous and ongoing, covering many aspects. This includes, but is not limited to, unbalance as a function of misalignment (and other faults) [4, 5], diagnosis of unbalance [6, 7], simulation approaches to aid unbalance prediction [8, 9] and lab based experimental investigations [10, 11]. Several detailed literature reviews exist detailing the scope of unbalance prediction research, including Edwards (1998), Foiles (1998), Randall (2004) and Walker (2011) [12-15].

Whilst the diagnosis of unbalance faults in rotating machinery has been detailed extensively in literature, comprehensive and practical solutions to the localization of unbalance are yet to exist in a form practical for many industrial applications.

Several numerical studies have been conducted into unbalance localization. Krodziewski (1994) details a system of obtaining balancing information without the use of test runs, through the



knowledge of mode shapes and modal masses [16]. Lees and Friswell (1997) extend this development through the measurement of pedestal vibration and a numerical model for rotor and bearing behavior [17]. The resulting system allows for unbalance state prediction through information obtained from both bearings in a dual bearing single rotor system. Whilst bearing damping factors are omitted from the study, the authors assert that the addition of this does not present any real difficulties.

Sinha (2002) further extends this development through assessment of unbalance state from information from a single run down. Theoretical models are in this case validated through a multiple disk/bearing test rig. The assessment is mostly concerned with unbalance amplitudes and phase information; however localization can also be performed through the collection of data from multiple bearing housings [18].

Saleem (2012) considers unbalance localization using a simple single bearing/rotor and overhung disk setup. This approach uses shaft deflection measurements in order to assess the unbalance state and position [19].

Walker (2012) discusses the potential use of NASTRAN and reduced order models in predicting the unbalance position through frequency response of the system combined with engine pass-off test simulations [20].

As mentioned, unbalance can be caused by a loss of blade material, resulting from a crack, rub, impact or other. This specific type of fault has been studied through the use of finite element approaches to localized variation in stiffness. Examples of this work include Mottershead (1999) and Feldman (1999) [21, 22].

Whilst the detailed work indicates potential methods for localizing unbalance in complex machinery, barriers to implementation still exist in this field. Referring back to the example of an aircraft gas turbine, it can be observed that limited sensor suites are currently implemented. This can often be limited to a single accelerometer placed at some distance from the rotating components, and subject to a noisy transfer path. As such, no defining method for localizing unbalance in situations such as this has appeared.

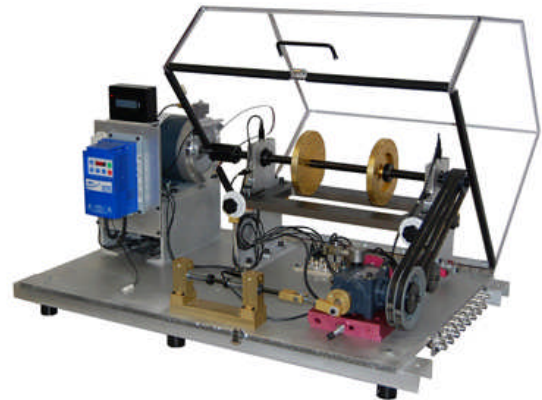
The work presented in this paper constitutes an investigation into the role of machine specific nonlinearities in rotating components for the purposes of unbalance localization. The wide range of nonlinearities which occur in rotating machinery can have significant effects on the vibration characteristics of a system. The study is based around a lab based rotordynamic rig (Spectraquest Machine Fault Simulator (MFS)) fitted with four disks for unbalance localization. The experimental results from the MFS have been complemented through the use of a second rotordynamic test rig containing different nonlinear features, for which the ANN has been adapted for use.

It is the intention of this work to detail the possibilities for nonlinear features to aid localization of unbalance faults in rotating machinery through a data driven approach. The subject of specific nonlinearities in rotating machines is a vast topic of research outside of the remit of this paper, which is instead

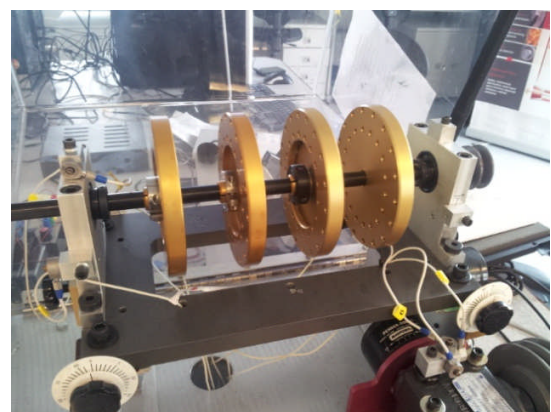
intended to outline through example an approach and methodology for improving localization in complex rotating machines through the use of a simplified sensor suite.

## DATA COLLECTION & ANALYSIS

In order to experimentally study the localization of unbalance faults, a Spectraquest MFS was fitted with four equally spaced discs as can be seen in figure 1. The MFS consists of two rolling element bearings supporting a single shaft connected to an electric motor through a flexible coupling. Data collection in this study is performed through the use of one single axis accelerometer, mounted in various positions (see 'Application of Artificial Neural Network'). Frequency components between 1Hz and 500Hz form the basis of this study. The relatively low frequency range is considered due to considerations for potential sampling, storing and processing constraints in real world applications. This frequency range also enables the first six harmonics to be studied for localization.



**Fig. 1(a): Spectraquest MFS**



**Fig. 1(b): Four disc MFS**

In order to fully interpret the collected data, some signal processing has been performed from the raw vibration data. Firstly, a fourth order Butterworth filter has been employed in order to restrict the data to the described frequency range. This

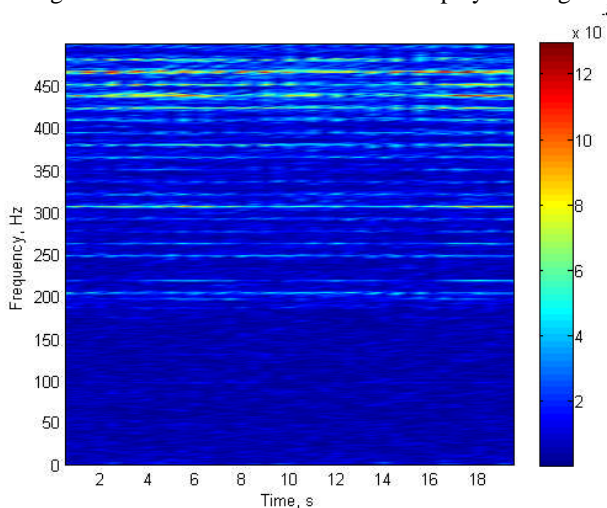
is achieved by cascading two second order low pass filters. The use of such a filter reduces the data required for processing, speeding up the application of ANNs (detailed later in this work). Butterworth low-pass filters are also commonly applied in order to reduce high-frequency random errors created through reconstruction.

Following on from this, conversion into the frequency domain has been utilized with the use of a Short Term Fourier Transform (STFT). This in turn enables harmonics to be studied in detail for different signatures between fault positions.

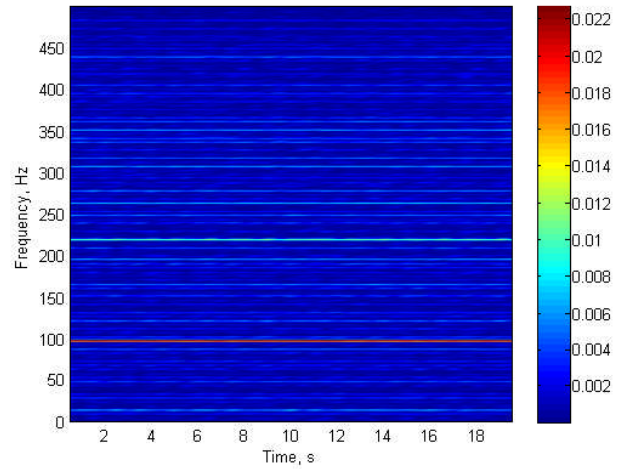
Further to this, small fluctuations in rotational speed (and therefore vibration amplitude) have been removed through the use of normalization. This is achieved through the division of the STFT value of each frequency with the norm of the STFT vector which contains the values of frequency. The normalized value for a particular frequency is determined using the following relation:

*Normalized value = value of amplitude/norm(frequency amplitude vector)*

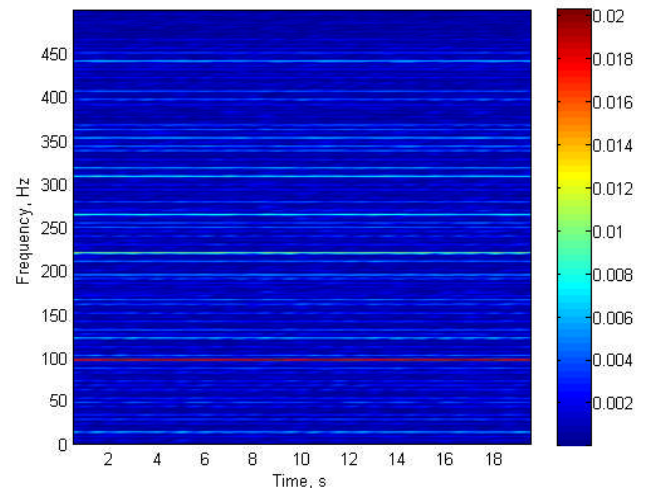
This preserves the relative strengths of the different frequency components in the frequency spectrum, which is important as this study involves assessing the relative strengths of the different frequency components in the spectrum. The normalization step is an important aspect in the processing. In order to consider the position of the unbalance fault it is necessary to consider the changes to the vibration phenomena to the system, and to negate the effects of unbalance size and position relative to the accelerometer. In this way, normalization can aid the understanding of the vibration phenomena occurring within a system. As one of the primary motives for this technique is operating with a reduced sensor suite, this provides the driver for such signal processing considered here. Finally, in an attempt to reduce noise in the acquired signal, a moving average filter has been applied. Using this configuration, spectrograms for each unbalance case are displayed in figure 2.



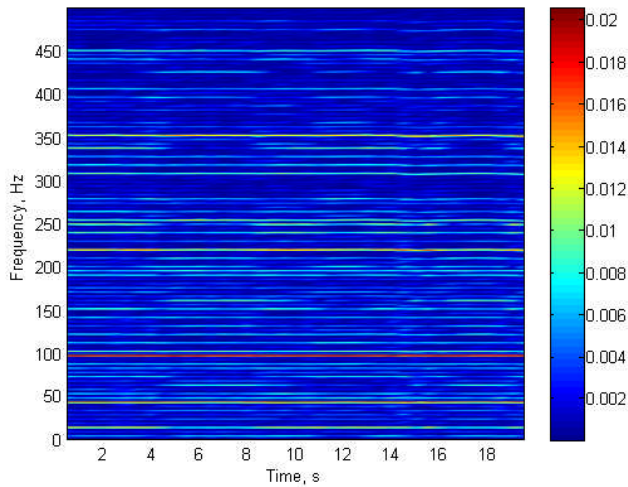
**Fig. 2 (a):** Balanced



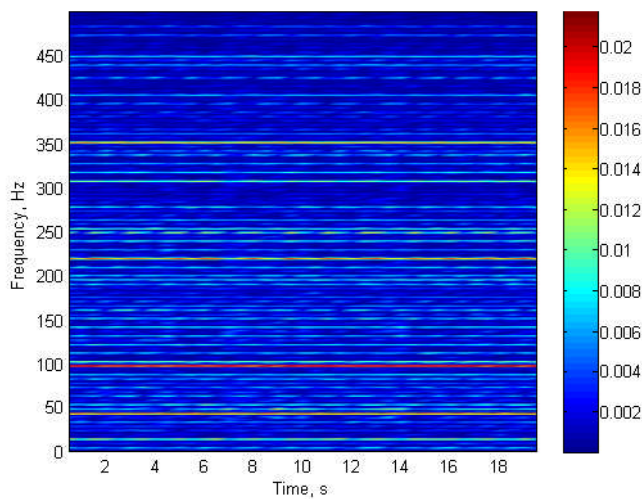
**Fig. 2 (b):** Unbalance on Disc 1



**Fig. 2 (c):** Unbalance on Disc 2



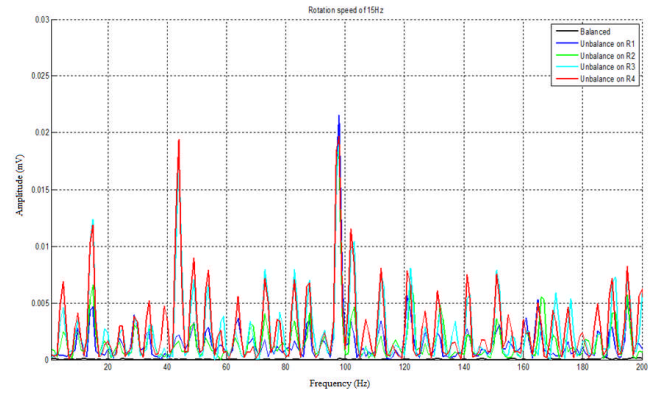
**Fig. 2 (d):** Unbalance on Disc 3



**Fig. 2 (e):** Unbalance on Disc 4

For the initial case of localization, a standard 8g static mass unbalance was applied to each disc in turn. ‘Disc 1’ refers to the disc mounted at the farthest point from the motor, whilst ‘Disc 4’ refers to the closest. In this initial case, the accelerometer is mounted on the bearing housing farthest from the motor. The study was repeated for a range of speeds (up to 45Hz). In figure 2 the case for 15Hz can be seen, with distinct variety in the different unbalance cases observed. It can be observed that over the 20 second collection period some periodic fluctuation in vibration amplitude remains. The harmonics which fluctuate in severity can be seen to differ from case to case, indicating the effects of the different unbalance cases on the nonlinearities within the system – a theory tested in the subsequent sections of this paper. Averaging the vibration amplitude across the 20 seconds of collected data yields figure

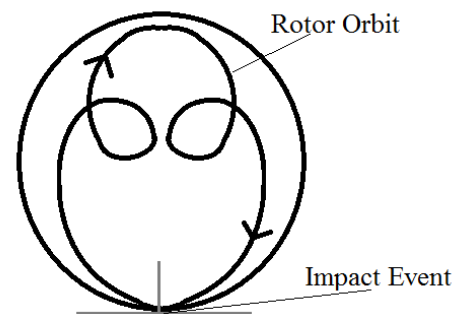
3, where the relative strengths of the amplitudes of the vibrational data are plotted.



**Fig. 3:** Pre-normalized frequency spectrum for unbalance localization cases.

Although figure 3 displays the expected result in that, in general, as the unbalance is closer to the accelerometer the amplitude of the harmonics is larger, the spectrum can be seen to be relatively complex. Distinct features exist within the studied range, displaying clear differences between the unbalance cases.

Upon investigation, the source of the nonlinear feature on the MFS rig was identified as a nonlinear feature arising from slight play of one bearing within the housing. A similar motion can be observed to occur in a chaotic motion under the case of oil whirl, in which such sub-synchronous harmonics are a common feature. In this case however, the whole rolling element bearing can be considered to move within the allowed tolerance of the housing – resulting in similar sub-harmonics, however due to an alternate bearing motion.



**Fig. 4:** Exaggerated example orbits of rotor and bearing within housing, corresponding to an impact event once every three rotations.

This type of nonlinear behavior has been described in literature by a number of authors. A detailed account has been made by

Muszynska (1995), where the authors extensively model such 'chaotic' responses, alongside experimental validation studies with regards to an unbalance force [31]. W.J. Wang (2001) details the use of nonlinearities for fault diagnosis purposes [32]. Ma, Hui, Tai (2011) detail this effect through a finite element simulation approach [33]. Qiu and Rao (2005) further discuss these phenomena using a fuzzy approach to an unbalanced rotor [34].

Whilst the linear approaches to unbalance classification are well established in theory, the effects of certain nonlinearities on unbalance are less well described. A wide variety of nonlinear effects are present in differing degrees in all rotating machinery. The degree of the specific nonlinearity identified for the MFS (which may itself be determined a fault if it was deemed to be above allowable tolerances in certain machines) may not be sufficient for fault localization to take place in many machines. However, it can be demonstrated that even a simple system such as the MFS contains sufficient nonlinear effects to aid localization, this potential can also be applied to larger, more complex rotating machinery.

For the case of the MFS, the design of the system (including easily removable/replaceable bearings) results in this nonlinearity being present to some degree even when the machine is operating under 'normal' setup conditions. The effect appears to be exacerbated by the support structure (a change in damping of the support structure appears to have a noticeable effect upon the nonlinearity). In this paper, the example results are taken at a rotation speed of 15Hz. It is clear that the speed has a distinct effect upon the vibration signature – however it was found that the one-third synchronous harmonics from the nonlinearity remain constant, with different unbalance cases remaining distinguishable within the measured range of 15Hz-45Hz.

## APPLICATION OF ARTIFICIAL NEURAL NETWORK

In order to automate the process of data analysis and comparison for the purposes of localization, an ANN has been employed. In this initial study, steady state (constant speed) operational data has been used as a simplifying factor for data collection. Such approach may be appropriate for certain types of rotating machine (e.g. power generation), whilst for others less so. ANN training on variable speed data (e.g. during run up-run down engine pass off tests) has been conducted in a number of studies [35-36], and due to the consistency of the nonlinearity and the linear harmonics in this case, it is envisaged that retraining the ANN for this case should contain no real difficulty provided time stamp data is available.

Numerous variations of ANN were studied, as a result of this process it was deemed that a 20 second set of data containing 500000 values could provide a suitable set of training data.

The ANN was trained using a back propagation algorithm which adjusts the weights of the connections of the network such that the outputs match the expected values. 156 signals for each type of unbalance for each speed value have been used.

For illustration, four speed values have been detailed (15Hz, 20Hz, 25Hz and 30Hz), however it should be noted that the work has also been conducted for a wide range speeds from 10Hz-45Hz, producing largely similar results to those detailed.

The initial case of ANN testing involved comparison of the different unbalance cases (static unbalance applied to each disc in turn), based upon the straight harmonics in the frequency domain (1X – 6X in integer values of X). This can be considered the 'linear' ANN, as the harmonics can be predicted by linear system models. These harmonics are present to some degree across the speed range due to the inherent inaccuracies and tolerances (including the inherent level of unbalance within the machine). The process of normalization detailed therefore enables these harmonics to be considered across the speed range. For this case two single-axis accelerometers on each bearing housing were applied for data collection, and this data does not include any sub-harmonic features.

The success of the ANN in predicting the state of the unbalance for the different cases can be seen in figure 5.

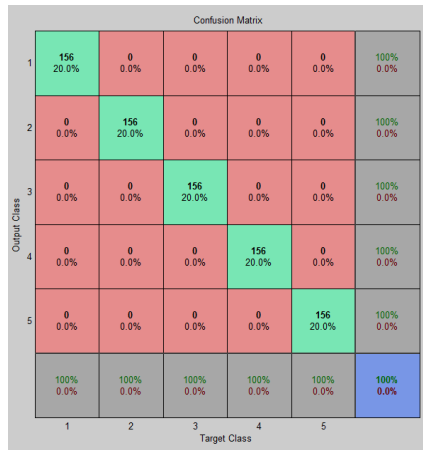
Rotor Speed	Disc 1	Disc 2	Disc 3	Disc 4
15Hz	75%	75%	70%	75%
20Hz	85%	80%	75%	80%
25Hz	85%	85%	85%	85%
30Hz	85%	80%	85%	80%

**Fig. 5:** ANN success rates for unbalance state prediction based upon 1X-6X harmonics ('Linear' ANN).

It can be seen that whilst the ANN includes a degree of success in localizing the unbalance, this is not sufficient to enable efficient unbalance localization. In an attempt to improve this, the effects of the detailed nonlinearity (and associated harmonics) were added to the ANN training. In this case the ANN assesses data from 1/3X, 2/3X, 1X, 4/3X, 5/3X and 2X – thus including the nonlinear features alongside the 1X and 2X harmonics. In figure 6 the confusion matrix for the training data, including accurate training and validation of the ANN, with 100% of samples being accurately classified.

	Disc 1	Disc 2	Disc 3	Disc 4
Disc 1	-	100%	100%	100%
Disc 2	100%	-	95%	100%
Disc 3	100%	95%	-	100%
Disc 4	100%	100%	100%	-





**Figure 6:** Confusion matrix for unbalance localization training. Row/column 1 = balanced disc, 2 = Disc 1 Unbalance, 3 = Disc 2 Unbalance, 4 = Disc 3 Unbalance and 5 = Disc 4 Unbalance

In figure 7 a marked improvement in the ability of the ANN to localize the unbalance fault can be seen, through the application of the nonlinear feature. This includes a 100% success rate when applied to the tested data range.

Rotor Speed	Disc 1	Disc 2	Disc 3	Disc 4
15Hz	100%	100%	100%	100%
20Hz	100%	100%	100%	100%
25Hz	100%	100%	100%	100%
30Hz	100%	100%	100%	100%

**Fig. 7:** ANN success rates for unbalance state prediction including nonlinear features ('Nonlinear' ANN)

Through training the ANN using the two methods mentioned ('Linear' and 'Nonlinear'), it can be seen that the addition of the nonlinearities is required for accurate localization. Following on from this, a series of further tests utilizing the ANN have been performed with the aim of demonstrating the advantages of utilizing the nonlinearities. The results of these are outlined as follows.

#### Sensor Positioning:

The above described tests were performed with one single axis accelerometer placed on each bearing housing. In the following tests, data collection was reduced to a single accelerometer placed on a bearing housing closest to the motor. Despite the reduction from two to one accelerometer, the accuracy of the tests remained at 100%. Finally, the single axis accelerometer was moved and tested at a number of remote positions (on the supporting structure). During the tests a comparison was made of the ANN including nonlinear features against the 'linear' ANN. It was found that the 'nonlinear' ANN demonstrated a maximum 5% loss in accuracy, whilst the 'linear' ANN displayed a loss in accuracy of up to 15%. The results of this test indicate the advantages of this system of localization in systems where sensor placement is limited. .

#### Multiple Plane Unbalance:

The initial testing detailed a single plain unbalance. In many cases of unbalance (a buildup of deposits on the disks being one example), unbalance appears in multiple planes. Within the relatively limited abilities of the MFS, the case of multiple plain unbalance was tested, with the following results for two-planes:

**Figure 8:** 2-Plane Unbalance ANN Results Matrix

The above displayed results include the ability to differentiate between single-plain unbalance. It can be seen that accuracy remains high for this case. In addition, three-plain unbalance was investigated, however due to operation limitations with such a high degree of unbalance; this testing was confined to low-speed testing. Despite this, accuracy for this case did not drop below 85%.

In a linear case, different unbalance distributions can appear to cause the same response (dependent on the speed and corresponding mode shape of the machine), thus reducing the ability to localize the unbalance. This issue can be limited through the addition of different accelerometers and the interpolation between the different vibration amplitudes observed. For case of the ANN with included nonlinearities, the complex effects of the nonlinearities at each bearing combined with the speed and modal information appear to combine in order to negate this effect. This therefore contributes to accurate unbalance localization using single speed and accelerometer data regardless of the unbalance distribution.

#### Noise:

Although considered a relatively simple test rig, the data collected from the MFS appears to be relatively noisy. Items such as the electric motor, surrounding electronic equipment (and mains supply) and other lab equipment contribute to this, in addition to the damping effects dependent on the surface on which the MFS is placed. Some of the noise was removed from this study through the use of filtering and consideration for minimizing noise from the surrounding environment. The amount of noise can be considered at least partially responsible for the low level of localization achieved through the 'linear' ANN. A comparison against a relatively noiseless system is detailed later in this paper.

#### Effect of Unbalance Size:

One of the potential issues of attempting localization with a single accelerometer is that of differentiating a small unbalance placed close to the accelerometer from a larger one placed further away. In the case of this study, normalization has been used in order to attempt to remove this effect from the system. Despite this, it is pertinent to assess experimentally the effect of unbalance size on the ANN. In order to do this, a series of test data was collected at three different unbalance weights (in addition to the standard weight). The results for the case of

15Hz can be seen in figure 9. All unbalance masses act at 70mm from the shaft centerline.

Rotor Condition	Disc 1	Disc 2	Disc 3	Disc 4
<b>5.0g</b> (Minimum)	45%	45%	50%	55%
<b>7.0g</b> (Light)	90%	100%	100%	100%
<b>8.3g</b> (Standard)	100%	100%	100%	100%
<b>10.1g</b> (Heavy)	100%	100%	100%	100%

**Fig 9:** Unbalance size effect on unbalance localization at 15Hz

It can be observed that the ANN is able to successfully localize the position of the unbalance fault to a high degree for all cases except that of the minimum unbalance weight. In this case, the ANN confused the minimum unbalance for the balanced condition. Whilst this indicates that the unique features of the one-third synchronous vibration enable accurate localization for the case of the MFS regardless of unbalance size, it is limited in the capability to diagnose small rotor unbalances.

#### *Effect of Unbalance Type on Localization:*

As part of this study, both unbalance type and unbalance localization have been considered. As highlighted, unbalance type can have a significant effect on the vibration spectrum of the MFS. Therefore combinations of unbalance type have been studied for the effects on localization. The results of this study are as follows:

Rotor Condition	Disc 1	Disc 2	Disc 3	Disc 4
<b>Static</b>	100%	100%	100%	100%
<b>Couple</b>	40%	50%	45%	50%
<b>Dynamic</b>	100%	100%	100%	100%

**Fig 10:** Unbalance type effect on unbalance localization at 15Hz

The indication from this set of results is that a dynamic unbalance (the most common form of unbalance) is able to be localized as well as the static conditions. However, couple unbalance is again confused with the balanced condition, for the same reasons as previously mentioned. This indicates that one of the main flaws in the proposed system is the ability to detect small cases of unbalance, either through the unbalance being too small to detect, or through incorrect rotor balancing efforts.

#### *Machine Rebuild:*

It is relatively common for the vibrational features of a machine to be significantly affected after heavy maintenance or rebuild. In order to replicate these phenomena on the MFS, the machine was dismantled, manually checked for any signs of wear, and then rebuilt back to the four disc specification. It was found that, after the rebuild, the ANN was unable to accurately localize unbalance using the existing set of training data. This problem was overcome through the process of capturing a new set of training data. After this, the ANN returned to the high level of accuracy previously detailed. This indicates that, in the

case of significant maintenance or machine rebuild, new training data will be required in order to maintain validity of the ANN. The ability to achieve this may vary significantly from system to system, and as such this topic is discussed in more detail in the discussion, along with the results from the other studies.

#### *Training Data:*

During the process of collecting results for this study, the need for accurate training data was realized. Collecting a number of samples, at the same operating conditions yields slightly different data. It was found to be imperative that the data used for training was clear and of good quality if a single data set was to be used. An alternate method to obtain accurate training data involved averaging a number of runs.

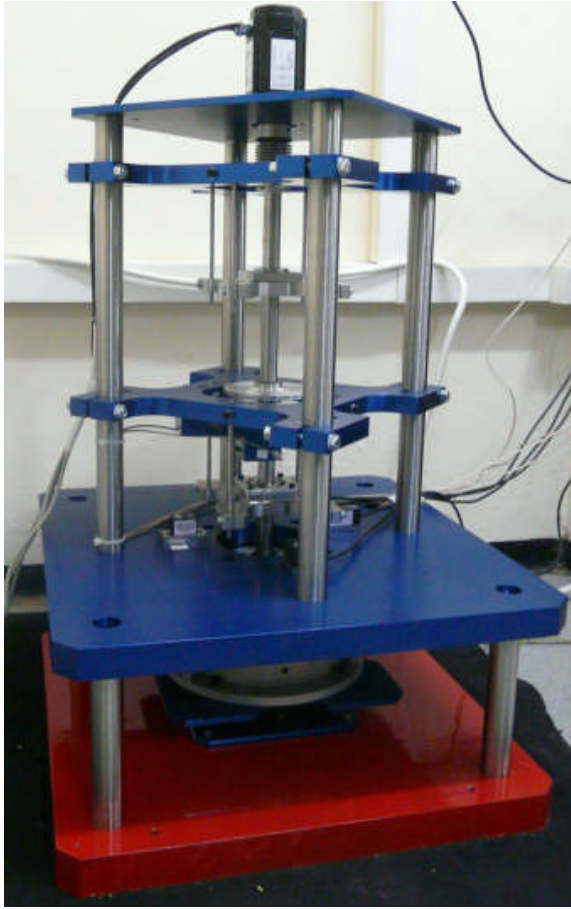
Collecting sufficient data in order to accurately train an ANN is a limitation of this artificial intelligence (AI) approach, in particular the collection of data for faults conditions. However, methods of reducing this limitation exist, dependent on the type of system under study. This is discussed in further detail later in the paper.

## **2<sup>ND</sup> RIG TESTING**

It has been demonstrated that the ANN has successfully been trained to localize unbalance across the four disc system of the MFS, with localization significantly improved through the application of subsynchronous nonlinear phenomena. In order to move this approach from a system specific application towards a general method for unbalance localization, the detailed ANN has been applied to a second rotordynamic rig. In this case, the rig varies significantly from the MFS, as can be seen in figure 11.

This setup includes two discs on a single rotor system, supported by two self-aligning ball bearings. In this case, unbalance is to be localized between the two discs. The procedure for setting up the ANN follows the same pattern, with a constant speed frequency spectrum first inspected for features. This can be seen detailed in figure 12, where the dominant peak of the 1X vibration plus the harmonics can be seen, in addition to some energy in the spectrum outside of these points. For the purposes of comparison, an ANN has been trained based upon the first six harmonics of the 1X vibration (1X – 6X), each for three conditions (Balanced, Unbalance Position 1 and Unbalance Position 2).

It can be seen from figure 12 that the operation of this rig is much smoother to that of the MFS, in part due to the smaller number of rotating parts within the system. In the case of the balancing rig, data collection is provided by two proximity probes – located on the support structure of the machine and remote from the bearing points. Data collection for the ANN follows the same format as that for the MFS. As this system consists of only two discs and is a low-noise system, the level of localization achieved through this approach was high. Despite this, 100% success across the tested data was not achieved, as can be seen in figure 13, with some error still occurring.



**Fig 11: Technion Institute Balancing Rig**

	Balanced	Unbalance Disc 1	Unbalance Disc 2
<b>8.3Hz</b>	100%	90%	90%
<b>16.7Hz</b>	100%	90%	95%
<b>25Hz</b>	95%	90%	95%
<b>33.3Hz</b>	100%	95%	95%

**Fig 13: 'Linear' ANN localization success rate**

Following on from this, a return to the frequency spectrum for the purposes of identifying nonlinearities can be performed. In this case, and as displayed in figure 12, at 1/6 rotation speed (~5.6Hz) a small peak of energy can be observed, from an unknown nonlinearity within the system. This small energy leakage appears to be affected by the unbalance state within the system. Whilst other sources of energy leakage appear to be present in figure 12, further analysis indicates that these features either vary with rotor speed or do not vary with unbalance position. Re-training the ANN in order to take into account the effect of this small nonlinearity yields the success rates detailed in figure 14

	Balanced	Unbalance Disc 1	Unbalance Disc 2
<b>8.3Hz</b>	95%	90%	90%
<b>16.7Hz</b>	100%	100%	100%
<b>25Hz</b>	100%	100%	100%
<b>33.3Hz</b>	100%	100%	100%

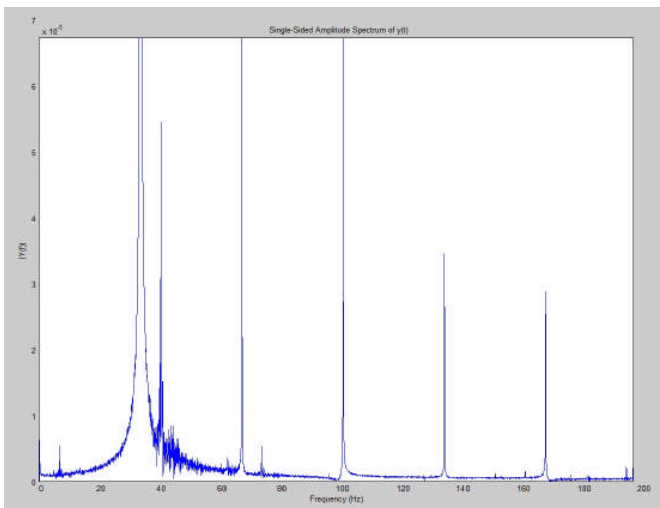
**Fig 14: 'Nonlinear' ANN localization success rate**

It can be seen that the ability of the ANN to localize the faults is once again improved by the inclusion of the nonlinearity into the system. In the case of 8.3Hz, this particular nonlinearity is masked by the dominant (1X) frequency due to the slow speed of the rotor, contributing to the reduced accuracy in localization.

Although further work is to be performed into this aspect of the research in order to fully interpret the behaviors of the balancing rig and the source of the nonlinearities present, the indications are that accurate localization can once again be achieved using inherent nonlinearities in the subsynchronous regime.

## LOCALIZATION METHODOLOGY

It can be seen from the detailed studies that a method of localizing unbalance has been determined and applied to two different rotordynamic test rigs. In both cases, subsynchronous nonlinear features in the frequency domain have been used in order to improve the fault localization through the application of an ANN. It is anticipated that such approaches have the potential for practical applications in the improvement of maintenance in complex rotating machines. The inclusion of nonlinear features appears to reduce the requirement for more advanced, expensive and potentially impractical sensor suites in order to achieve the same level of localization. In addition, the

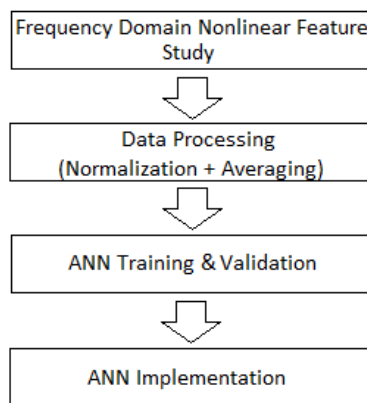


**Fig 12: Single sided amplitude spectrum at 33Hz speed**

nonlinear approach to unbalance localization has several advantages over the linear approach.

The complex interactions caused by the unbalance fault on the nonlinearities of the machine results in specific vibration spectrums dependent on the unbalance case. In the linear domain, these interactions are predictable and repeatable. A simple example of this is indicated by a small unbalance placed close to the accelerometer, which can display an almost identical linear response to an equivalent larger mass placed further from the sensor. Depending on the machine, the interactions between the structure, nonlinear bearing effects, fault position and other effects enable each unbalance case to be considered with a specific response, thus enabling the improved accuracy over the linear approaches.

This preliminary investigation within the scope of possibilities on such relatively simple rigs indicated a high level of localization achieved for both single and multiple planes and different unbalance distributions on a single plain across a wide range of speed and unbalance size. Based upon this, the method applied for localizing unbalance in such rigs can be demonstrated as follows.



**Fig 15: ANN Implementation**

One potential limitation of the system for application beyond test rigs is the inherent limitation of data collection for the purposes of training an ANN. This limitation is discussed by a number of authors including [37-38]. One potential approach to circumnavigate this limitation involves the collection of faulty operating data for one system, whereby trending data is then applied to a similar system. This is an avenue of research in the field of gas turbines in particular, wherein the potential exists to seed faults and collect training data for specific (often previous generation) turbines fitted to test rigs. The study of localization and nonlinear features can then be inferred for later generations of turbine. The latest developments into finite element modeling of whole engine models [39, 40] alongside nonlinear simulation techniques [41, 42] are beginning to provide scope for developments in this area.

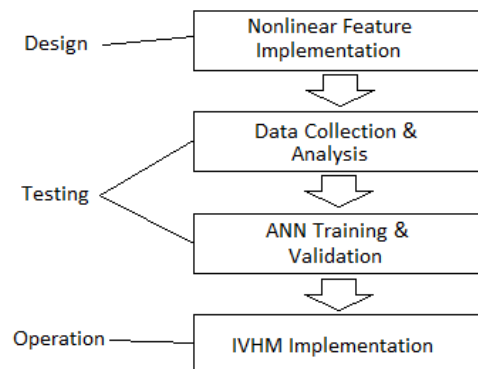
One further limitation with the detailed system of localization includes an inability to accurately diagnose unbalance under certain conditions, such as small unbalance weights or couple

unbalance. In some systems, even a small unbalance outside of the given tolerance can be seen to be unacceptable (no machine is perfectly balanced). One possible solution to this problem, requiring further study, is the combination of a separate system to diagnose unbalance in the first instance (as discussed, many of these have been researched). Upon detection of the unbalance, the localization ANN could be run. This would have the effect of removing the balanced case from the equation, thus forcing the ANN to determine a disc for the unbalance.

## ROTORDYNAMICS & IVHM

The field of IVHM is subject to much current focus in research, as the drive towards comprehensive vehicle and fleet wide health monitoring solutions gains momentum. This includes all aspects of vehicle health monitoring, from diagnosis, prognosis and localization algorithms to energy harvesting and on board/off board optimization [2]. The field of rotordynamics has an important part to play in the development of the field of IVHM. The drivers behind localizing unbalance faults have been highlighted, however it is important to note how such localization techniques can potentially fit into the broader picture of IVHM.

It can be noted that the localization techniques outlined rely on existing nonlinearities within the system in order to aid localization. One potential avenue of research which has recently begun to be explored is that of design for IVHM. The theory that a controlled design feature (or, in this case, nonlinearity) could be incorporated into a turbomachine from the design phase, in order to aid diagnosis, localization and prognosis of faults. This enables significant advantages for techniques such as that detailed in this paper, whereby sensor suites can be reduced, whilst an improved level of localization can be achieved. A board framework for implementing such a system would look as follows:



**Fig 16: Design for IVHM (Localization)**

Many further aspects require study in order for a viable solution to be implemented in an industrial application. This includes aspects as wide as data handling and processing and incorporating diagnosis, prognosis and localization of other rotordynamic faults. Despite this, the potential exists for a



system of localization similar to that outlined to form an important part of future IVHM systems.

## CONCLUSIONS

The research outlined in this paper presents a novel methodology for improving unbalance localization through the use of nonlinear subsynchronous features in the frequency domain. Through the application of the nonlinearities to an ANN, a series of unbalance types have been localized on two differing rotordynamic testing rigs, with a high level of accuracy achieved. It is proposed that such approaches to unbalance localization provide benefits in the form of reduced/minimal sensor suites whilst enabling improved maintenance actions across complex systems. It is envisaged that techniques such as that outlined could be best implemented through a 'design for IVHM' approach, therefore forming part of future vehicle and fleet wide IVHM systems. As such, future work in this area is aimed at achieving this ultimate goal.

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